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Constructing a framework for analyzing the reliability and value of uncertain seismic interpretations

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Constructing a framework for analyzing the reliability and value of uncertain seismic interpretations

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Dedication

To my family for their endless support and inspiration. To Maxine for her love and confidence.

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Abstract

Constructing a framework for analyzing the reliability and value of uncertain seismic interpretations

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Exploration geology is built upon the use of seismic data to image strata of sedimentary rocks to search for hidden wealths of petroleum resources deep under the Earth's surface. Although this method is ubiquitous, it is imperfect and inherent uncertainties arise from various sources including the acquisition, processing, and interpretation of such data. Making absolute assessments of such reserves is often difficult, and decisions to effectively manage these uncertainties are further complicated as a result. It is important to understand how uncertainties affect the exploration process, and how they can be evaluated, mitigated, or accommodated in order to optimize economic decision making to maximize value in these scenarios. An area in need of development in this optimization process is to quantify the reliability of seismic interpretations to measure how dependable this imperfect information can be. This study will include a review of work that has previously been done on the uncertainty and value of seismic information for exploratory purposes and a proposal of a framework by which these concepts can be used to guide decision making. Ultimately, this work will enable project managers and decision

makers to make more informed choices in the face of uncertainty to optimize the success of future exploration projects.

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Chapter 1. Background and Motivations

1.1 A History of Petroleum Exploration

In 1859, a serendipitous find revolutionized the United States of America and inadvertently kick-started an entire industry that still forms the basis of the modern age. Near Titusville, Pennsylvania on August 27 of 1859, a well was dug to a depth of 69 feet before it struck oil (Brice 2009). This historic find was the result of an effort led by Colonel Edwin Drake, and so it bears his name and is today known as the Drake Well. At the time, this discovery was important as it provided an alternative to coal in the production of kerosene that was cheaper and possessed a higher potential yield than coal. Though an important resource in this regard, it was not until the invention of the automobile in 1886 that petroleum became a dominant force in the energy mix. In spite of these material benefits, the ultimate legacy of the Drake Well was more profound. The success of this well emboldened other explorationists to drill more wells to exploit this resource, thus giving rise to the modern petroleum industry.

In spite of the revolutionary status of the Drake Well, the means by which it was explored was surprisingly basic. In lieu of sophisticated geological models or advanced technology, Drake based his exploration efforts on the crude method of identifying an area with a significant rate of hydrocarbon surface seepage (Curtis et al. 1981). In the nascent stages of the petroleum industry, such a simple and trivial practice was sufficient for early explorationists. But with growing demand and increased consumption, the maturing industry sought out more oil fields which called for more sophisticated methods.

A wide range of geological models and technology have been employed in the hunt for oil since the days of Drake. Early methods such as the anticlinal theory became guiding maxims with the discovery of the Spindletop oil field in the Gulf Coast (Chance 1886; Lerner and Lerner 2003). Other fields of study such as geological mapping, stratigraphy, and sedimentology provided powerful insights that conferred a predictive power to the search for hydrocarbons that enabled researchers to make inferences and refine models of deposition to better represent the form and behavior of reservoirs in the subsurface. In addition to these geological concepts, a suite of geophysical methods were developed that provided explorationists with additional tools to assess the hydrocarbon potential of a prospect. Beginning around the 1920s, geophysical applications of seismology, gravity, magnetism, and borehole methods provided a more in-depth method of imaging conditions at depth that layered details upon the framework created through geological study (Lerner and Lerner 2003). Altogether, these concepts and technologies have provided explorationists an expansive toolkit with which to probe the subsurface.

In the modern age, no other discipline is more widely used or offers more insight into the subsurface than reflection seismology. The first noted application of an experiment to utilize sound waves propagating through the Earth to study the subsurface occurred in 1921 in Oklahoma (Dragoset 2005). This experiment, later to be known as the Vines Branch experiment, demonstrated that seismic waves produced by a dynamite charge were able to produce an image of the subsurface. Better yet, this image even aligned with geologic features already known at the time! In spite of this stepping stone, the initial image results were low resolution. In the decades since, major developments such as common depth-point acquisition, vibroseis, 3-D, and even 4-D surveys have established reflection seismology as the standard in petroleum exploration. In spite of the significance of seismic data, the method is far from perfect. Even with the most advanced technologies and extravagant budgets, decision-makers utilizing seismic data must make decisions in the face of uncertainty. Although this unenviable task may not have an answer in the fields of geology and geophysics, another discipline known as decision analysis provides the necessary tools to address this deficiency.

1.2 History of Decision Analysis

Although the term "decision analysis" entered the academic lexicon in 1966, the concepts and principles that compose the foundations for decision analysis were laid out decades, and in some cases even centuries, before. From the 18th century, decision analysis drew upon two important thinkers involved in probability theory, Abraham de Moivre and Reverend Thomas Bayes (Skinner 2001). De Moivre advanced an empirical, frequentist approach to probability in that for an infinite number of trials, the number of successes of a particular event will converge to a specified value. For illustrative purposes, it is from this tradition that the familiar example of a coin toss draws from. It is not unheard of for a coin flipped twice to land either heads up twice or tails up twice. Were the coin to be flipped ten times, it would be much more unlikely for the coin to land in the same orientation for all trials than in the previous case. Extending this example ad infinitum would result in the familiar result in which half of the coin tosses land heads up and the other half tails up. Although this idea is familiar to most individuals, an inherent flaw of this line of thinking lies in the concept of infinite trials, which is infeasible in real world settings, let alone in those in which finite resources are involved. The Bayesian approach to probability forgoes the notion of infinity and empirical observation. Instead, probability is interpreted as an expectation of the results of a trial. In this sense, the Bayesian approach to probability has had more influence on decision analysis by casting probability as a statement of one's belief. Another important contribution to the foundations of decision analysis was offered by John von Neumann and Oscar Morgenstern in the mid-20th century with the publication of their book The Theory of Games and Economic Behavior. The primary significance of this text is as a landmark of game theory, but the authors also devote a chapter to the discussion of the use of utilities as a measure of preference of multiple outcomes. Because decision makers are called upon to discern between possible courses of action with uncertain outcomes, it is imperative that they have a consistent method with which to value and order their preferences.

In a seminal paper, "Decision Analysis: Applied Decision Theory", Howard laid out "a formal procedure for the analysis of decision problems" (Howard 1966). The succinct manner in which Howard was able to encapsulate the essence of decision analysis underscores its applicability to real world problems in which many of these principles may be already be in practice, but without a quantifiable or rigorously structured basis. Howard was able to weave many of these important concepts into a framework that is well suited for study in an academic setting, practical application in corporate environment, and even use in one's personal life. In a sense, Howard's formalization of these principles already practiced was a method to apply engineering discipline to the often hazily defined space of decision making. Among these achievements in the seminal paper were a formal definition of a decision, a clearly outlined procedure for analyzing decisions, a discussion on the notion of probability, uncertainty, and subjectivity, and recommendations for professional practice.

1.3 Applications of Decision Analysis in the Petroleum Industry

Although the techniques and tools of decision analysis are applicable to any cases in which decisions are involved, they are of particular interest to certain projects and industries. To understand why this should be the case, it is helpful to think about the factors that may make the prospect of employing decision analysts attractive or unattractive (Howard 1980). To begin, the hiring of decision analysts and the time required for them to execute their analyses is a consumption of the familiar resources of time and money. Furthermore, analyses are naturally limited, since it is impossible to model every potential outcome. Lastly, the quality of the analysis is dependent upon the practitioner, and an unskilled or ill-intentioned analyst is capable of producing poor results. In spite of these potential pitfalls, the true value of decision analysis is present in its ability to bring immersion value and examinability to complex decision situations. The immersion value refers to the ability to incorporate all of the important factors that may influence the decision. The examinability aspect involves the fact that the elements of the analysis are quantitative and explicit. These qualities allow for the results of the analysis to be independently reexamined and for insights to be gleaned. As a result of these trade-offs, decision analysis is most useful in industries in which large investments must be made in projects with a high degree of complexity arising from factors including, but not limited to, uncertainty, the interplay of many variables, the actions of potential competitors, and the existence of many possible courses of action. Examples of such industries include pharmaceutics, manufacturing, and of course, oil and gas.

The petroleum industry is an ambitious endeavor that is as much science as it is business. Furthermore, decisions that have the potential to earn or lose up to hundreds of millions of dollars are almost always made in the face of great uncertainty. As described previously, these characteristics make it a prime candidate for decision analysis. Before the conception of this field, however, the industry relied upon less sophisticated methods for guiding important decisions. These methods included more direct methods such as a direct calculation of an average rate of return on invested capital. Because such methods are largely deterministic, there is not much allowance for risks and uncertainty, which was remedied by the introduction probabilistic models, Monte Carlo simulation, and decision trees (Newendorp 1975; Coopersmith et al. 2000). Taken altogether, these concepts can bring a more enlightened perspective to every facet of the exploration process including cost estimation, reserve evaluation, and production forecasts (Neal and Krohn 2012). The high costs of exploration, drilling and production coupled with the uncertainty of petroleum resource sizes, recoverability, and oil and gas prices make the application of decision analysis a natural fit for the industry.

A particular aspect of decision analysis that is especially relevant in the petroleum industry is that of the value of information (VOI) (Bratvold et al. 2007). In spite of the major advancements that seismic technology has brought to the industry, it is innately imperfect as seismic data do not directly reveal the presence nor absence of hydrocarbons. Instead, the behavior of the returned waves indirectly inform explorationists by recording the behavior of the waves reflected from the layers of the subsurface. In addition to this disconnect between the test (seismic survey) and the uncertainty of interest (presence, absence, and amount of oil in place), seismic data are subsequently processed and interpreted, introducing the variable of human judgment into the equation. Lastly, these data are subject to human judgment once again, and perhaps to its greatest extent, in the interpretive stage. With these many junctures with the potential to obscure a clear understanding of the subsurface, crucial questions that decision-makers must be cognizant of is how reliable are these interpretations and to what degree they can be trusted. The VOI approach is ideal for answering these questions as it quantifies the impact that information of varying qualities can have on decision-making.

1.4 Objectives

The objective of this study is to present an interdisciplinary approach that calls to attention the need for explorationists to better understand the uncertainties embedded within their interpretations and to adjust their beliefs accordingly.

1.5 Methodology

This study will largely survey previous work that has been done in the various disciplines concerning the exploration process and the sources of uncertainty inherent to seismic interpretation. To this end, the thesis will begin with an overview of the petroleum system and methods of evaluating exploration prospects. It will be followed by an introduction to reflection seismology, a subdiscipline of geophysics that forms the foundation for the seismic data used to image the subsurface. Following these technical primers is a duo of chapters examining sources of uncertainty and error that may muddle an interpretation. We then move on to a discussion of the value of seismic information that includes a theoretical basis as well as a literature review of the subject. Finally, we integrate these various subjects to create a platform for incorporating uncertainty about interpretation into a decision-making process.

Chapter 2. The Geology of Petroleum Systems

2.1 Elements of a Petroleum System

The petroleum system concept is an important principle that guides exploration by uniting different concepts and elements of petroleum geology under a common framework (Magoon and Beaumont 1999). In its most general sense, a petroleum system is defined as a source of petroleum and the accumulations of oil and gas that are genetically related to the source. These systems are often found in layers of sedimentary rock that are subjected to structural changes that are conducive to the concentration of hydrocarbons over geologic time. In order to generate and house these accumulations of oil and gas, these systems must possess four necessary elements.

2.1.1 Source Rock

In order for petroleum to be present, there must be a suitable source of the building blocks required for its formation. This requirement in a petroleum system is satisfied if there is an adequate source rock, which is rock capable of producing or had previously produced a significant amount of hydrocarbons. This quality of the source rock potential is itself subject to three criteria (Law 1999). First, the rock must have a sufficient quantity of organic matter. Second, the rock must be capable of yielding moveable hydrocarbons. Third, the rock must have achieved thermal maturity through burial and diagenesis after sedimentation. These conditions are most commonly met by shales that are deposited in low oxygen environments that experience upwelling and rapid sedimentation.

2.1.2 Reservoir Rock

Though petroleum originates in source rock, these rocks have traditionally not been the primary targets from which oil and gas are produced. This is due to the low porosity and permeability characteristic of shales which greatly impedes the flow of hydrocarbons through such layers. Instead, oil and gas are often produced from reservoir rocks, rocks which are capable of storing fluids such as hydrocarbons within their pores. A good reservoir rock is typified by relatively high porosity and permeability that are conducive to production from these layers. The most common examples of reservoir rocks are sandstones in clastic systems and porous, permeable limestones in carbonate systems.

2.1.3 Seal

Due to the buoyant nature of petroleum relative to water, oil and gas rise from deep in the Earth until they reach the surface or meet an obstruction. Situations in which hydrocarbons rise unobstructed and reach the surface result in the occurrence of oil and gas seeps. In spite of their occurrence, such seeps are more of an exception rather than a typical example of what happens to oil. In more practical and economically exploitable cases, petroleum is usually contained in a reservoir rock in the subsurface due to the presence of a seal, a layer of impermeable rock such as shale that halts the continued ascent of oil in the subsurface. The configuration of a seal overlying a reservoir rock establishes the geometrical shape of the accumulation of oil and gas deposits.

2.1.4 Overburden

The final element in a petroleum system is the overburden rock, the sedimentary rock which overlies the reservoir and seal, which has an important function as a facilitator of hydrocarbon production. A necessary step in the diagenetic production of petroleum is the application of heat and pressure to the organic content present in the source rock. These diagenetic changes are largely due to the deposition of the overburden rock which buries the source rock under an increasingly thick column of rock. As this column grows, the source rock experiences deeper burial, and the associated increase in heat and pressure from the geothermal gradient and the overlying sediment cause the organic matter in the source rock to convert into hydrocarbons.

2.2 Petroleum System Processes

Beyond the physical elements which constitute a petroleum system, the term also encompasses the related processes that led to the formation and accumulation of hydrocarbons within the system. Chief among these processes are trap formation and the generation, expulsion, and migration of the hydrocarbons (Magoon and Beaumont 1999).

As previously alluded to in the discussion about the seal, the buoyancy of petroleum mobilizes the hydrocarbons, and without an adequate means to impede their movement, oil and gas can potentially be lost from the system. The presence of a seal is just one feature of the means by which this loss can be averted. A more complete approach to how these hydrocarbons are kept in place is through the analysis of traps and their formation. A trap is a geometric arrangement of a reservoir and a seal that allows for the accumulation of oil and gas (Vincelette et al. 1999). Broadly stated, the two main types of traps are structural traps and stratigraphic traps. A structural trap is formed through the effects of folding and faulting of rock layers in the subsurface after deposition of the source rock. Stratigraphic traps are the result of deposition of varying types of sediment that result in a configuration that effectively stores hydrocarbons.

After being subjected to temperature and pressure due to the effects of overburden, organic matter in the source rock is converted into oil, which as previously discussed, is more buoyant than the water in which it resides. The hydrocarbons preferentially flow from positions of higher potential energy to lower potential energy, which causes them to follow a predictable migration pathway (Matthews 1999). The original expulsion of hydrocarbons from their source rock is termed primary migration. Subsequent migration of hydrocarbons upon leaving the source rock and moving through the reservoir is termed secondary migration. Buoyant forces cause hydrocarbons to migrate vertically until encountering a sloping surface and then are deflected updip. The final accumulation of hydrocarbons in the reservoir as a result of this process is dependent upon the formation of an effective trap. Without such features, the hydrocarbons would continue to migrate until they reach the surface. The breaching of the surface by the escaped oil and gas is called tertiary migration. The final example of a possible migration pathway is remigration in which hydrocarbons move from one reservoir position to another within the same reservoir or into another reservoir. Though all four migration pathways are known to occur, the most important processes in a productive petroleum system are primary and secondary migration.

2.3 Geologic Risk

Collectively, a petroleum system illustrates the pieces of a puzzle necessary to form an effective and producible accumulation of oil and gas. The definition and assessment of a petroleum system thus far has been a purely qualitative. As described, a petroleum system can provide a method to screen the potential of a reservoir. One proposed remedy to this shortcoming was introduced by Otis and Schneidermann (1997) in a paper which outlined principles of geologic risk assessment that could be applied to quantify the geologic risk, the probability of the presence of a reservoir. The probability of geologic risk (P_g), is dependent upon four familiar factors:

(1) Presence of a source rock (P_{source})

(2) Presence of a reservoir rock ($P_{reservoir}$)

(3) Presence of a trap (P_{trap})

(4) Play dynamics ($P_{dyanmics}$)

These four risk factors are closely related to the elements laid out in the petroleum system framework. The source and reservoir are assessed according to the qualities previously described. The presence of a trap is affected by the quality of the seal and the processes of trap formation. Lastly, the play dynamics are assessed based upon the qualities of the overburden and the processes that shaped the petroleum system. The most important determinants of these factors are tabulated below.

A. SOURCE ROCK

1. Capacity for HC charge (within fetch area)
   - Presence and volume of source rock
     - Thickness
     - Areal extent
     - Number of distinct source horizons
     - Continuity
     - Known HCs in area (fields, wells, seeps)
   - Organic richness (TOC, S_1+S_2, etc.)
   - SPI
   - Kerogen type
     - Type I - lacustrine, oil prone
     - Type II - marine, oil & gas prone
     - Type II - gas prone
     - Type IV - Inert
2. Source rock maturity
   - Source rock data (R_o, T_{max}, E1)
     - Determine whether source rock in fetch has generated HCs

B. RESERVOIR

1. Presence
   - Lithology
   - Distribution
   - Depositional model (sequence stratigraphic framework)
2. Quality (Capacity for stabilized flow)
   - Lateral continuity and extension
   - Thickness and vertical cyclicity
   - Heterogeneity
   - Porosity ranges and types
   - Permeability ranges and types
   - Fracture potential and preservation
   - Diagenetic characteristics

C. TRAP

1. Trap definition (confidence in data)
   - Number and location of seismic lines
   - Quality (resolution) of seismic data
   - Reliability (velocity complications, misties)
   - Lateral velocity gradients
   - Integration of gravity, magnetic, seismic and well log information
2. Trap characteristics
   - Type of trap (anticlinal, fault, etc.)
   - Amount of four-way closure
   - Amount and type of other closure
   - Compartmentalization by faulting
   - Alternate non-closing interpretations
3. Seal
   - Top seal
     - Lithology and ductility
     - Thickness
     - Continuity
     - Curvature over trap
     - Degree of fracturing or faulting
   - Fault seal
     - Fault type
     - Amount of throw
     - Time(s) of movement
     - Depth and pressure
     - Lithologies juxtaposed
     - Dip of beds across fault
     - Potential for sealing gouge
   - Stratigraphic seal - bottom or lateral
   - Other seals - diagenetic, pressure, etc.

D. TIMING AND MIGRATION

1. Timing
   - Timing of reservoir, seal and trap development relative to that of HC generation and migration
   - Maturation model (burial history, paleogeothermal regime)
   - Thermal gradients (BHT, heat flow, lithology)
2. Migration Pathways
   - Position of trap with respect to kitchen/fetch area
   - Amount of source rock in the oil window within fetch area
   - Migration style (vertical or lateral)
   - Migration distance required (vertical and lateral)
   - Migration conduits and barriers/migration style
   - Connection of pathways to reservoir
3. Preservation/Segregation
   - Post entrapment tectonism or faulting
   - Displacement of oil by water or gas
   - Biodegradation
   - Thermal cracking
   - Preferential migration of gas

Table 1. Geologic risk assessment checklist (Otis and Schneidermann 1997).

These four factors can be assigned a value ranging from 0 to 1 that translates the qualitative assessment of each factor into a numerical value. A 0 in this rating system represents certainty that a necessary factor is absent, whereas a 1 represents certainty in the presence of a factor. These ratings are based upon the results of data analyses as well as the confidence in the data quality. A table summarizing how these values describe an explorationist's judgment is given below.

Risk Assessment	Probability Range of Risk Factor Occurrence	Qualitative Interpretation
Favorable	0.7 - 0.99	Direct data that support the presence of a geologic risk factor
Encouraging	0.51 - 0.7	Indirect data that support the presence of a geologic risk factor
Neutral	0.5	Inconclusive data that neither support nor refutes the presence of a geologic risk factor
Questionable	0.3 - 0.49	Indirect data that refute the presence of a geologic risk factor
Unfavorable	0.01 - 0.3	Direct data that refute the presence of a geologic risk factor

Table 2. Quantitative measures of qualitative interpretations for geologic risk assessment.

Given assessments of these four factors, the probability of geologic risk can be calculated by multiplying their associated probabilities.

$$P_g = P_{source} * P_{reservoir} * P_{trap} * P_{dynamics}$$

Two important insights arise from this equation. First, the absence of any one factor eliminates the potential for oil under this system. This relationship is analogous to that of the links in a chain, in which a break in one link leads to failure of the entire system (Rose

1987). Second, the multiplication of these decimal values quickly decreases the probability of geologic success. For example, even a rating of 0.9 in each factor will result in a probability of just 0.6561 for geologic success.

Reexamining Table 1 reveals the significance of seismic information in assigning probability assessments of each of these factors. Each of the four factors depends upon seismic information to varying degrees. The original table developed by Otis and Schneidermann (1997) and reproduced by Garcia (2002) is adapted in Table 3 below to highlight the significance of seismic information in this endeavor. Sub elements and their parent elements that incorporate seismic data into their assessment are bolded for clarity.

Geologic Factor	Elements	Sub elements
Source Rock	**Capacity for HC charge (within fetch area)**	**Presence and volume of source rock** • **Thickness** • **Areal extent** • **Number of distinct source horizons** • **Continuity** • Known HCs in area (fields, wells, seeps)
		Organic richness (TOC, S_1+S_2, etc.)
		SPI
		Kerogen Type • Type I – lacustrine, oil prone • Type II- marine, oil & gas prone • Type III – gas prone • Type IV – inert

Table 3. Significance of seismic information in geologic risk assessment (adapted from Otis and Schneidermann 1997; Garcia 2002).

	Source rock maturity	Source rock data (R_o, T_{max}, E1) Determine whether source rock in fetch has generated HC
Reservoir	**Presence**	Lithology
		Distribution
		Depositional model (sequence stratigraphic framework)
	Quality (capacity for stabilized flow)	**Lateral continuity and extension**
		Thickness and vertical cyclicity
		Heterogeneity
		Porosity ranges and types
		Permeability ranges and types
		Fracture potential and preservation
		Diagenetic characteristics
Trap	**Trap definition (confidence in data)**	**Number and location of seismic lines**
		Quality (resolution) of seismic data
		Reliability (velocity complications, misties)
		Lateral velocity gradients
		Integration of gravity, magnetic, seismic, and well log information
	Trap characteristics	**Type of trap (anticlinal, fault, etc.)**
		Amount of four-way closure
		Amount and type of other closure
		Compartmentalization by faulting
		Alternate non-closing interpretations
	Seal	**Top Seal** • Lithology and ductility • **Thickness** • **Continuity** • **Curvature over trap** • **Degree of fracturing or faulting**

Table 3 (continued).

		Fault Seal • **Fault type** • **Amount of throw** • Time(s) of movement • Depth and pressure • Lithology juxtaposed • **Dip of beds across fault** • **Potential for sealing gouge**
		Stratigraphic seal – bottom or lateral
		Other seals – diagenetic, pressure, etc.
Timing and Migration	Timing	Timing of reservoir, seal, and trap development relative to that of HC generation and migration
		Maturation model (burial history, paleogeothermal regime)
		Thermal gradients (BHT, heat flow, lithology)
	Migration pathways	**Position of trap with respect to kitchen/fetch area**
		Amount of source rock in the oil window within fetch area
		Migration style (vertical or lateral)
		Migration distance required (vertical and lateral)
		Migration conduits and barriers/migration style
		Connection of pathways to reservoir
	Preservation / Segregation	**Post entrapment tectonism or faulting**
		Displacement of oil by water or gas
		Biodegradation
		Thermal cracking
		Preferential migration of gas

Table 3 (continued).

Analysis of this table shows that all four factors and eight of ten elements draw upon seismic information in some shape or form. This illustrates the significance of reflection seismology within this geologic risk framework in the explorationist's toolkit.

Chapter 3. An Introduction to Reflection Seismology and Seismic Survey Design

3.1 A Reflection on the Basics of Seismic

In spite of the complexities, nuance, and jargon, the most fundamental aspect of reflection seismology is front and center in its name. The term "seismic" references the discipline's study of wave propagation through the medium that is the Earth, and the term "reflection" specifies which behavior of the wave propagation that explorationists are most interested in. Taken as a whole, this terminology reveals that at its core, seismic exploration is merely a study of the behavior of induced sound waves that reflect off layers in the subsurface in order to elucidate information about the properties of the material below.

In order to best visualize how such waves can reveal so much information, it is helpful to imagine an analogous scenario as illustrated by Unruh (1987). A blind man is lost in the desert and has no bearing about his surroundings save for the presence of a cliff in his vicinity. By clapping his hands, he is able to generate a sound wave that expands radially until it interacts with the cliff reflecting back to the man as an audible echo. With knowledge about the speed of sound through air, an impeccable ear for timing, and mathematical know-how, the blind man is able to calculate the distance between himself and the cliff. However, as this is only one data point, he knows only that the nearest point of the cliff lies somewhere along a circle with a radius equal to the calculated distance away from himself. In order to better understand the geometry of the cliff face, he must repeat this process multiple times from different positions in order to create more of these reference circles to constrain the possible shape of the cliff face. Through this process, the blind man can observe features that he could not directly visualize. Though this example may appear to be a crude analogy, it actually demonstrates many key aspects of a seismic survey. In a seismic survey, the initial clap is represented by a source, whether it be from a dynamite charge or a vibrating source; the unseen cliff face is replaced by the rock layers and target geobodies in the subsurface; and lastly, the blind man's ears which hear the echo are substitutes for the geophones which record the response. These examples each include a transmitter, a receiver, and a means to calculate distance given time elapsed between the transmission and reception. Collectively, these elements constitute an echo-ranging system (Coffeen 1978).

Although the echo-ranging system has undeniable utility, the ability to calculate distances to different reflecting surfaces underground is only telling a portion of the story. For exploratory purposes, it is necessary to also learn about the behavior of the reflected wave. This information can be gleaned from a calculation of the reflection coefficient, which is given by the following equations (Ashcroft 2011):

$$Reflection\ Coefficient = RFC = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1}$$

in which:

ρ_1= density of the upper layer

v_1 = velocity of a sound wave through the upper layer

ρ_2= density of the lower layer

v_2 = velocity of a sound wave through the lower layer

Though relatively simple in appearance and calculation, these equations hold valuable insight into rock properties and the resultant wave behavior upon interaction. In order to fully appreciate these equations, it is helpful to step back and recognize the nature of the seismic waves of interest in this scenario. Seismic waves are a class of sound waves, which are waves that propagate through a medium through successive pulses of compression and decompression (Coffeen 1978). The amplitude of these compressions and decompressions are directly related to the energy of the original source. Furthermore, the speed at which the wave propagates is dictated by the medium through which it is travelling. In denser materials, the constituent molecules are packed more closely together, and so sound travels quicker. In less dense materials, the opposite is true, in which the loosely packed molecules transmit sound less quickly. Together, these two principles can be applied to the reflection coefficient to investigate rock properties. The sign of the reflection coefficient of an interface describes the phase of the wave, with a positive value indicative of a compression wave and a negative value indicative of a decompression wave. A returning compression wave is characteristic of a transition from a denser medium to a less dense medium. On the other hand, a returning decompression wave represents a transition from a less dense medium to a denser one. The magnitude of the coefficient describes the amplitude of the wave. A high density contrast will result in a large amplitude whereas a low density contrast will have a low amplitude.

These two concepts, echo-ranging and the reflection coefficient, are only the tip of the iceberg that is reflection seismology. However, they provide a basis for understanding the rationale behind the interpretation of seismic data, which is the end goal for a seismic survey in petroleum exploration. In this sense, the success of a seismic survey is dependent upon a high quality seismic survey. This brings up the question, however, as to what constitutes a high quality seismic survey and how dutifully should it be trusted. In order to explore this question, it is necessary to step back from the data interpretation phase and reassess the conditions of data acquisition. A high quality seismic survey is one which possess a high signal-to-noise ratio (SNR). The signal, which is a physical measurement of a real geological phenomenon, should be maximized. On the other hand, noise, which includes all the extraneous sources of interference which confound the signal, should be minimized.

3.2 Stacking and Fold Coverage

One of the key breakthroughs in the evolution of seismic acquisition and processing was the development of the common-depth point (CDP) technique. Before its conception, all points in a seismic survey were represented by only one source and geophone pairing. This setup had an inherent weakness in that it was highly susceptible to noise. Worse yet, the only option to reduce the noise in this scenario was through band-pass filtering the trace which also diminished the signal (Dragoset 2005). The CDP technique provides an elegant solution to these problems. By modifying and manipulating the geometry of the arrays of equipment, it was possible to produce configurations in which a given point in the subsurface could be imaged by multiple source and geophone pairings. Each pairing would produce a separate measurement for that same point of interest, and the number of such pairings would come to be known as the fold for that point. The resultant seismic record produced by adding up traces from multiple recordings through this approach is called a stack (Pritchett 1990). A stack provides a means to hedge against noise because the multiple recordings would likely reinforce the presence of a real signal, while an incidental anomaly in one measurement would be dampened. The CDP method, then, provides a realistic and practical method to maximizing the SNR through good seismic survey design.

Because of the importance of the fold to the SNR, it is a worthy measure of the quality of a seismic record. An explorationist working with a single-fold data set may identify an anomaly in his section that is characteristic of a reservoir. However, he would be wise to be suspicious of the anomaly as there is a significant probability that it is merely noise. With such a low fold, it is difficult to have confidence in the data, and interpretability is accordingly low. On the other hand, an explorationist working with a high-fold data can identify the same anomaly in his own data set would be more confident in his findings as much of the noise in the data would have accordingly been filtered out through data processing. As a result, a high fold data has a correspondingly high interpretability. The relationship between fold and interpretability is illustrated in the graph below.

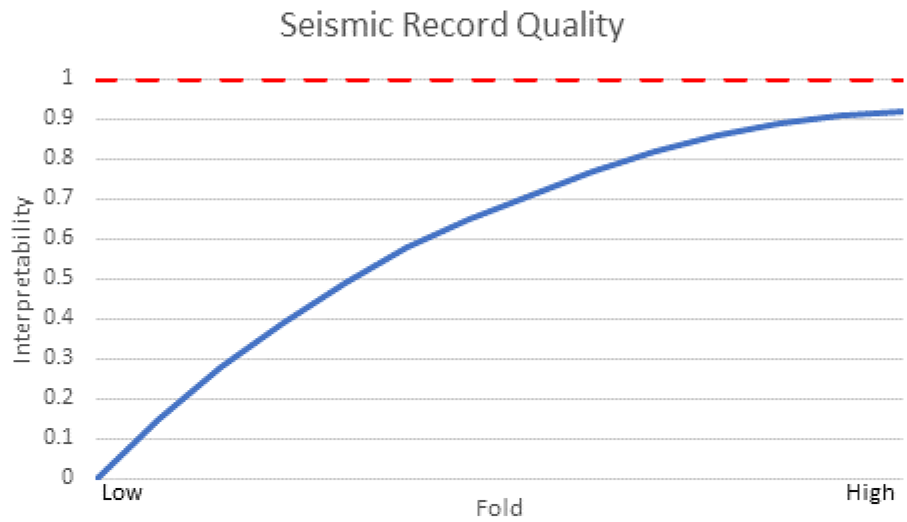


Figure 1. Fold coverage and interpretability

There are a few worthy discussion points that are raised by this graph. First and foremost is the omission of labels for the fold axis. This graph is meant to be a generalized depiction, and the required fold to reach the same level of interpretability in different settings will vary dramatically. The second point to be made is that the scale of interpretability runs from 0 to 1, where 0 occurs only as a lack of data to be interpreted. On the other hand, an interpretability value of 1 is treated asymptotically since this represents a scenario in which perfect information is achievable, there is no uncertainty at all about the subsurface, and anyone with a trace of familiarity could identify any potential reservoirs in the section. Another point illustrated by this graph is that in the absence of considerations such as cost, a higher fold is always preferable to a lower fold because of the increase in the SNR and resultant interpretability. The last and most profound insight gleaned from this graph concerns the rate of change. At low fold values, an increase in the fold results in a large increase in the interpretability. At increasingly higher values, however, the incremental increase in interpretability decreases. This phenomenon of diminishing returns imposes an economic constraint on the fold. At some point, the improvements in interpretability will be outweighed by the incremental cost to acquire a higher quality data set. This tipping point is of utmost importance for decision makers seeking to maximize value in an exploration venture.

Chapter 4. Uncertainty in Geological Interpretation

4.1 The Subjective Nature of Interpretation

One of the most fundamental and challenging aspects of utilizing seismic data in the search for hydrocarbons is innate to the field of geology as an interpretive science. In any geoscientific discipline, challenges encountered include the incompleteness of data (owing to gaps and poor resolution of the stratigraphic record), the lack of experimental control available to laboratory-based sciences, and the time spans required for geological processes to unfold which makes observation difficult. These challenges betray the notion that science is, as Frodeman (1995) puts, a "certain, precise, and predictive" process for acquiring knowledge about the natural world. Instead, Frodeman posits that geology should be viewed as an interpretive science based on the principles of hermeneutics, the theory of interpretation.

Three major concepts of hermeneutics are applicable to geology. The first of these is the idea of the hermeneutic circle, which describes the circular flow of knowledge, in which parts are understood in the context of a whole, and concurrently, the whole is understood as the entirety of its parts. This apparent paradox can be explained and clarified through example. Seismic data has previously been described as a major component in developing models for use in exploration. At the same time, this model that results, at least in part, from the interpretation of seismic data may encourage an interpreter to revisit the seismic data with the model in mind for reexamination of strengths and weaknesses of the model. This iterative back-and-forth helps the interpreter glean more insight about both the part and the whole.

The second concept of hermeneutics is a set of three prejudgments, or "fore-structures", a term which Frodeman (1995) attributes to the philosopher Martin Heidegger (1962). These fore-structures are so called because they constitute a set of predispositions that any inquirer brings to the geological problem. The first of these fore-structures is the preconception, which is the ideas and thinking one brings to a study. The second of these is foresight, which is the presumed goal or notion of an acceptable answer an inquirer believes about the problem at hand. The last of these prejudgments is fore-having, which constitutes the skills and tools used to analyze a situation. These predispositions can be seen at play in an exploration setting by considering two differently trained explorationists exposed to the same set of seismic data: one a cautiously pessimistic stratigrapher, the other an optimistic structural geologist. The stratigrapher may determine that the observed stratal terminations do not form an adequate trap in a zone of interest, and therefore there is a low potential for oil in this reservoir. On the other hand, the structural geologist may conclude that the extensive faulting creates a sufficient trapping mechanism leading him to conclude that this same reservoir dismissed by the stratigrapher is a good prospect.

The final hermeneutic concept relevant to geology is that of the historical nature of human understanding. This concept is closely related to the preceding fore-structures which states that the conclusions reached in a scientific study are largely influenced and shaped by the set of preexisting knowledges, attitudes, skills, and tools each individual brings to the study. As a result, it is impossible for interpreters to reach some final, objective understanding of reality that some scientists aspire to achieve. Instead, each interpretation is a subjective culmination of the individual's fore-structures.

Although the discussion thus far has been largely philosophical, there are important implications of this interpretive nature of geology for the exploration process. The most salient of these is that given a single problem, different individuals will likely reach different conclusions that can have wildly different models and valuations. These differences do not necessarily lead to the complete invalidation of all but one correct interpretation. Instead, there are likely valuable truths offered by each interpretation. It is the job of a decision-maker to weigh the merits of these conclusions to produce a model which best incorporates these truths to succeed in the exploratory endeavor. To ably assess these strengths and weakness, it is helpful to understand how uncertainties arise.

4.2 Factors Affecting Interpretation

The seismic images that explorationists utilize are the end result of a long process with many junctures requiring human input and judgment calls. The decisions made in the acquisition and processing of seismic data are important to the final success of the final decision to be made, but here I focus on the sources which contribute to uncertainty in the interpretations of these resultant seismic images.

As previously discussed, the processes that guide each interpreter's approach to a given problem are grounded in the individual's set of fore-structures. This notion is illustrated in a study by Macrae et al. (2016) in a survey of 444 geoscientists. The survey consisted of a single seismic data set which participants were asked to interpret and identify key geologic features. The results were then compared against the interpretations submitted by reference experts who were recognized as experienced leaders in interpretation, structural geology, sedimentology, and tectonics. The results of the participants' interpretations were scored according to their identification of key structures highlighted by reference experts. It is important to note that because real seismic data was used in this study, there was no singular, correct answer about the subsurface. However, the convergence of the different experts upon key geologic features increases confidence that these interpretations are a realistic model of the subsurface. The seismic image used in the survey and the reference image composited from the experts' interpretations are included in the figure below.

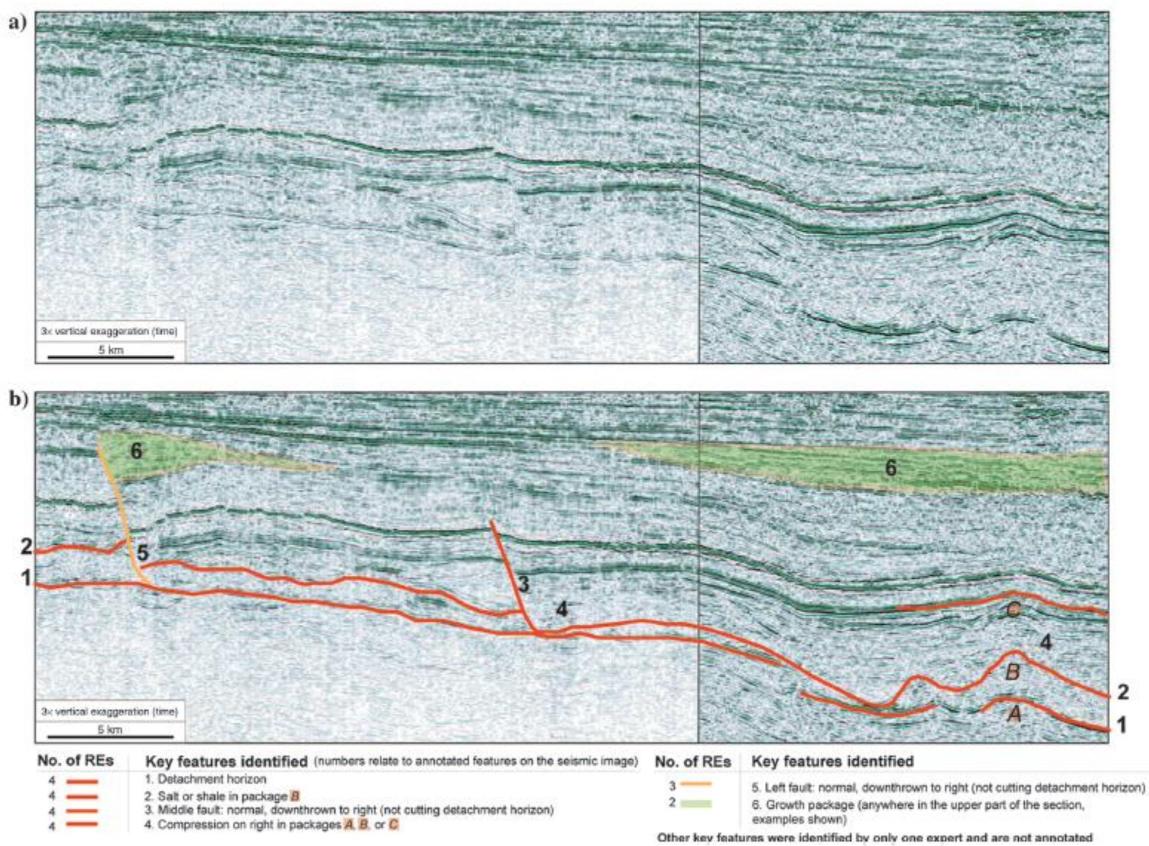


Figure 2. a) Seismic test data and b) expert-interpreted standard of comparison (Macrae et al. 2016)

The researchers behind this study concluded that a set of four background factors and five interpretational techniques were most significant in producing a high quality interpretation. The findings of their analysis are summarized below.

Background Factors	Experience in structural geology
	Frequency of seismic image interpretation and use
	Background in a super-major or major oil company
	Number of geographic locations worked in
Interpretational Techniques	Incorporated geologic time in interpretation
	Drew cartoons to illustrate relevant processes
	Wrote about geological processes
	Clearly stated relevant processes
	Drew arrows to specify fault movement

Table 4. Factors Relevant to a High-Quality Seismic Interpretation (Macrae et al. 2016)

The work done by Macrae et al. 2016 demonstrate that the fore-structures and prejudgments interpreters bring with them can drastically affect their success at making sense of seismic data. As a result, interpretations made by individuals with backgrounds and that incorporate these techniques should be weighed favorably against those that do not.

Another study by Alcalde et al. (2017a) reinforce the findings of Macrae et al. (2016) by analyzing the effects of background knowledge on seismic interpretation. In this study, a group of about 70 masters students were tasked with interpreting a set of seismic data before and after a training module focused on structural geology. The data set, which is included in the figure below, was depicted in both two-way travel time and depth.

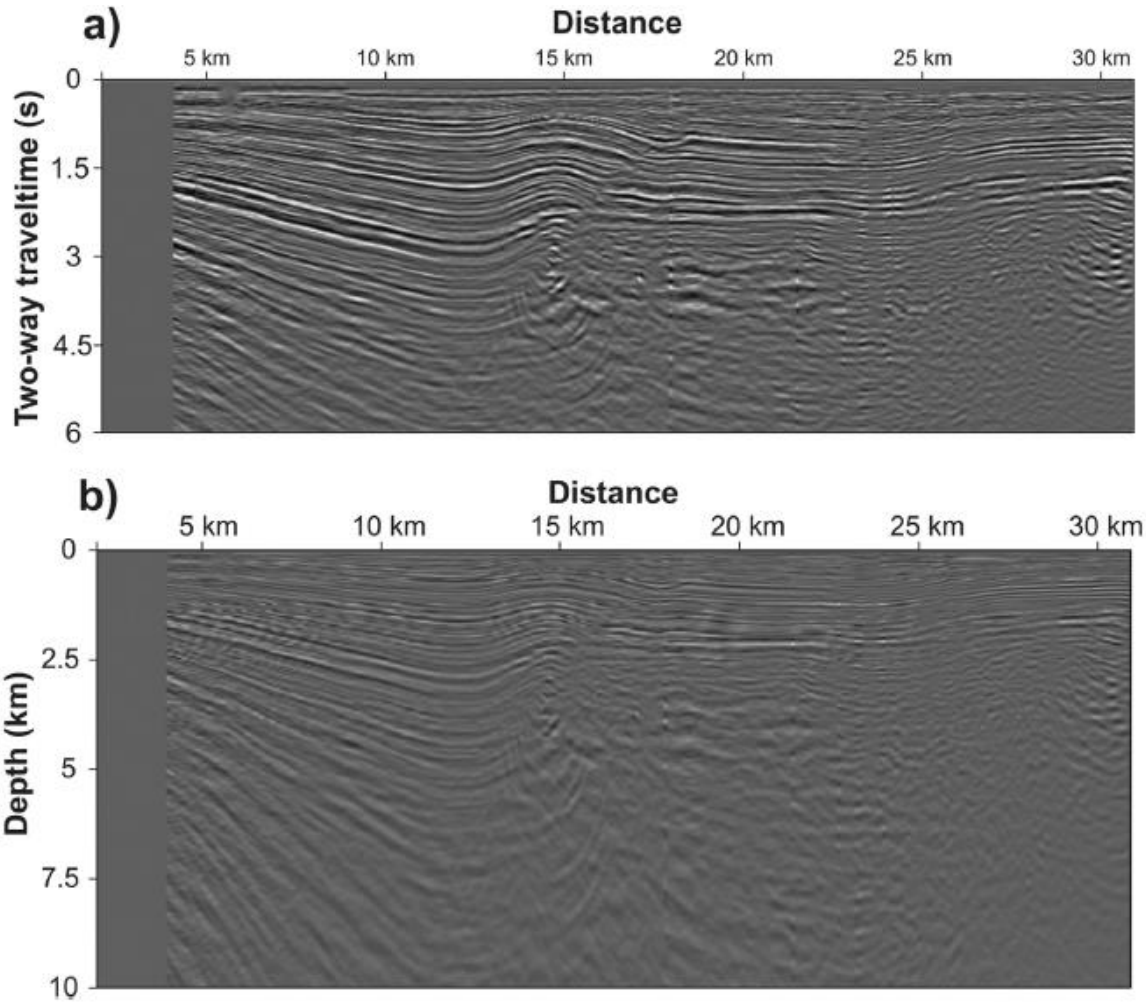


Figure 3. Seismic data used in interpretation exercise displayed in (a) two-way travel time and (b) depth by Alcalde et al. (2017a).

The results of this experiment illustrated a marked difference in the students' assessments of their proficiency at seismic interpretation as well as their interpretations of the data set before and after they had participated in the course.

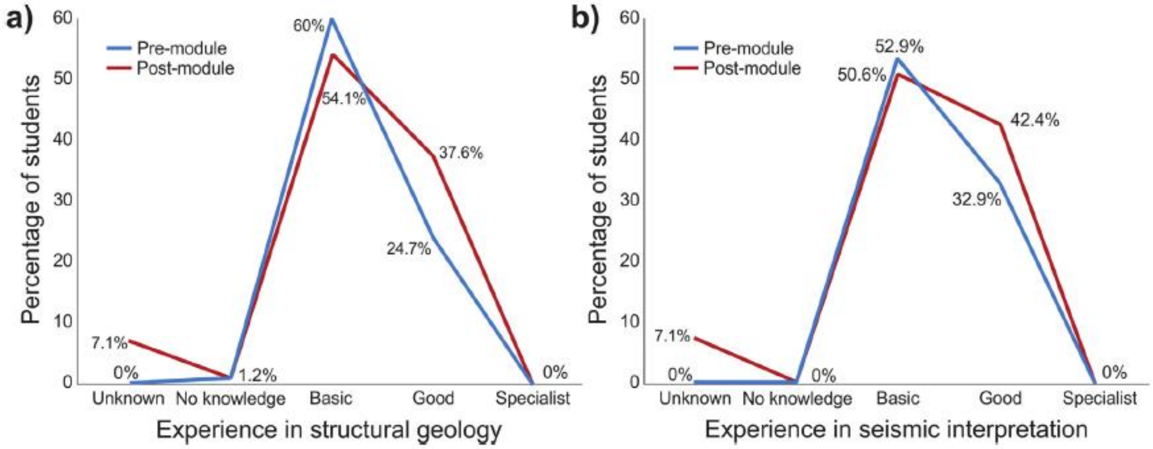


Figure 4. Self-assessment of structural geology and seismic interpretation experience by students before and after participating in a structural geology training module (Alcalde et al. 2017a)

Prior to the course, 60% of students described their experience with structural geology as "basic" and 24.7% described their experience as "good". After the course, the portion of students claiming "basic" knowledge decreased to 54.1% as the portion describing their experience as "good" rose to 37.6%. Similarly, the students determined that the module had increased their experience in seismic interpretation. Prior to the module, 52.9% of students described their experience as "basic". This portion decreased to 50.6% following the course as the portion of students describing their experience as "good" increased from 32.9% to 42.4%.

While the increase in student confidence in interpretation is heartwarming, the more interesting story concerns the types of interpretations made about the structural features observed in the data set. The results of the students' interpretations of fault types is included below in Figure 5. Prior to the module, students were more likely to describe faults as normal and reverse faults, which are overrepresented in a survey of textbooks surveyed by

Alcalde et al. (2017a). Following the module, students diversified their classification. The proportion of faults described as normal and reverse decreased, while the number of inversion faults nearly doubled. In addition, students described more faults as undefined.

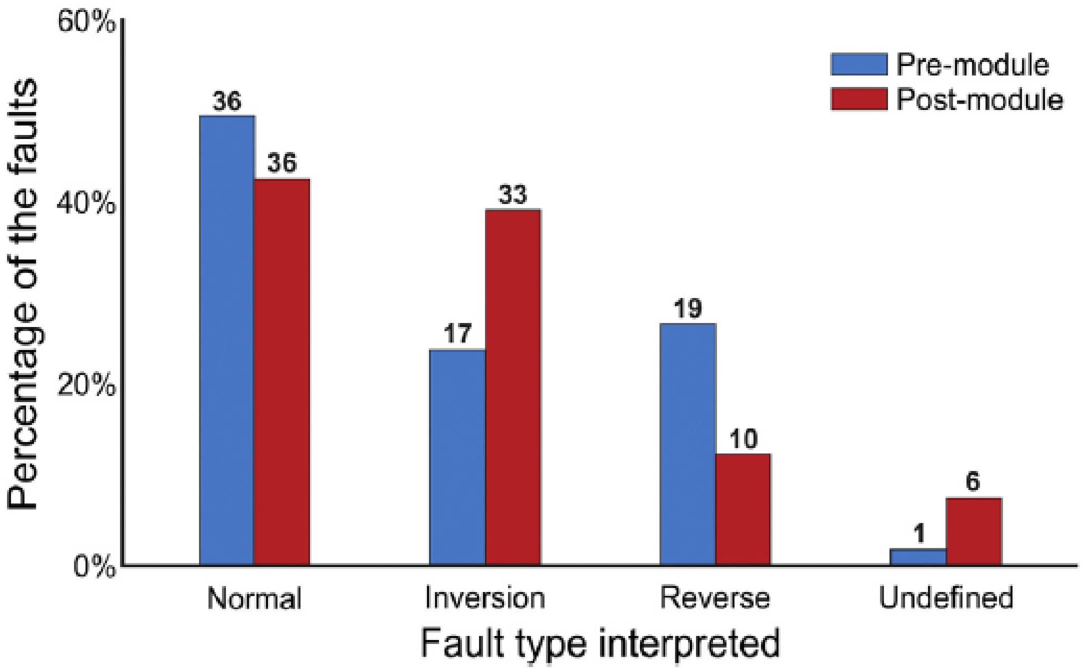


Figure 5. Fault type interpretations by students before and after participating in a module on structural geology. (Alcalde et al. 2017a).

The overrepresentation of normal and reverse faults in textbooks, the self-assessments made by the students about their experience, and the proportion of fault types classified combine to demonstrate a psychological pitfall that can have major effects on interpretation. The inexperience of the interpreters led them to overestimate the proportion of normal planar faults in the data. The researchers attributed this phenomenon to the emphasis of textbooks and educational material on these types of faults and to availability bias. The availability bias is a tendency for an individual to inflate the importance of a familiar idea, concept, or example that is easy to recall (Tversky and Kahneman 1974).

Though this example concerned just one specific discipline applied in petroleum exploration, the malleability and variability of interpretations based upon the background knowledge available affects all interpretations of incomplete data.

Beyond the subjective nature of interpretation which can lead to different interpretations of the same data by different individuals, decisions made in preparing the data can also vary interpretations. In a separate survey administered to 196 interpreters of diverse backgrounds and utilizing the same data set previously discussed, Alcalde et al. (2017b) used the contrasting image qualities to highlight how the quality of data available could also lead to divergent interpretations. The seismic images used for the survey as well as the results of the interpretations are provided in Figure 6.

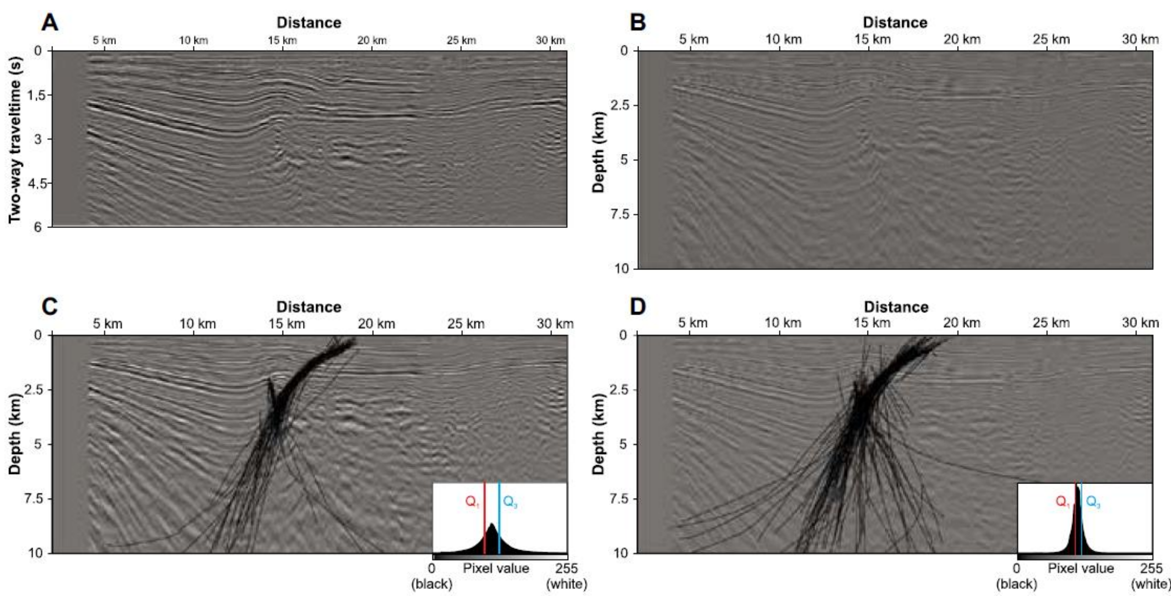


Figure 6. The effect of image quality on seismic interpretation. (a) Seismic image in two-way travel time, (b) Seismic image in depth, (c) Aggregated interpretations pre-module, (d) Aggregated interpretations post-module (Alcalde et al. 2017b)

These two images portray the same set of data processed in the same manner save for the depth conversion required to translate the data from two-way travel time into a linear measurement. The quality of these images was manipulated to emphasize differences in pixel intensity contrast and reflection continuity. Contrast was analyzed by assigning pixel values ranging from 0 (black) to 255 (white) and counting the distribution of values. Continuity was analyzed by setting a threshold dividing the range of pixel values into two halves, with all pixels below the threshold set to black and vice versa. The length of these resultant black and white reflectors was then used to determine reflector continuity by length.

Based upon these metrics, the seismic image portrayed in two-way travel time was determined to have three times greater contrast that the image portrayed in terms of depth as determined by the interquartile range of pixel value distribution. In both images, continuity decreased with depth and to the right of the fault. However, the reflectors in the depth image were 63% shorter on average in the depth image relative to the two-way travel time image. The decreased contrast and continuity of the depth image resulted in greater uncertainty as evidenced by the greater variance in fault interpretations assigned in Figure 6(d) relative to Figure 6(c). This study demonstrates that, in addition to fore-structures, factors external to the interpreter can drastically affect confidence in geologic models based upon seismic data.

4.3 Multiple Working Hypotheses

As a result of the subjectivity of interpretation, compounded by the intrinsic and extrinsic factors that may influence it, it is possible for multiple models to be developed from the same seismic data set that all honor the data. Though no more than one proposed model (perhaps even less than one!) for a given problem may be entirely correct, the existence of these multiple interpretations may be more of a boon than a bane (Chamberlin, 1890). In developing just one model, there may be a subconscious bias to simultaneously exaggerate the importance of details that support the theory and downplay the impact of those that weaken the theory. Instead, the method of multiple working hypotheses posits that the multitude of potential, testable possible models encourages thoroughness and impartiality in examination of the available evidence. In spite of this benefit, the original problem, that no more than one of these models may perfectly explain the phenomenon, remains. Decisions cannot be made based upon the existence of multiple models, and so taking advantage of the method of multiple working hypotheses for petroleum exploration requires keeping an open mind while working towards the establishment of a model that reconciles the uncertainties that distinguishes interpretations.

Chapter 5. Pitfalls Present in Seismic Data

In addition to the problems previously discussed concerning the uncertainty embedded in interpretation, the medium of seismic data is also inherently subject to errors due to its indirect imaging of the subsurface. These errors, known as pitfalls, are false structures associated with velocity changes in the subsurface, geometry inconsistencies in representing a three-dimensional space in a two-dimensional slice, or technical distortions from recording and processing (Tucker and Yorston 1973). Though these pitfalls arise through different mechanisms and manifest themselves in the seismic data in different ways, they share a common potential to mislead interpreters. This section will review some examples of these pitfalls to further illustrate potential lapses in seismic reliability.

5.1 Pitfalls Associated with Velocity

The first category of pitfalls concerns the changes of seismic wave velocities as the waves travel through and interact with different media, including both rocks and fluids in the subsurface. Because these waves do not provide direct observation of the subsurface layers' constituents, the returned signal can easily be misread and misattributed. The simplest example of this misattribution of seismic velocity occurs when interpreters mistakenly attribute the seismic signature of one feature for another. This misunderstanding can have costly consequences, as evidenced by an analysis by Mawdsley et al. (1997). This example is taken from south-central Alberta, a region in which Lower Cretaceous clastics are known to overlie Upper Paleozoic carbonates. In this region, incised valley sandstones in the Cretaceous package are common exploration targets. In this case, a suspected sandstone was identified through a seismic response consisting of two amplitude anomalies. First, the amplitude at the top of the feature of interest showcased an amplitude twice the magnitude of an adjacent trough. Second, there was a significant amplitude increase in the peak below the feature of interest. These features are observable in Figure 7 below. However, it was recognized that interpretations in the Cretaceous clastic package could be made difficult by constructive interference from structural highs in the underlying Paleozoic unconformity.

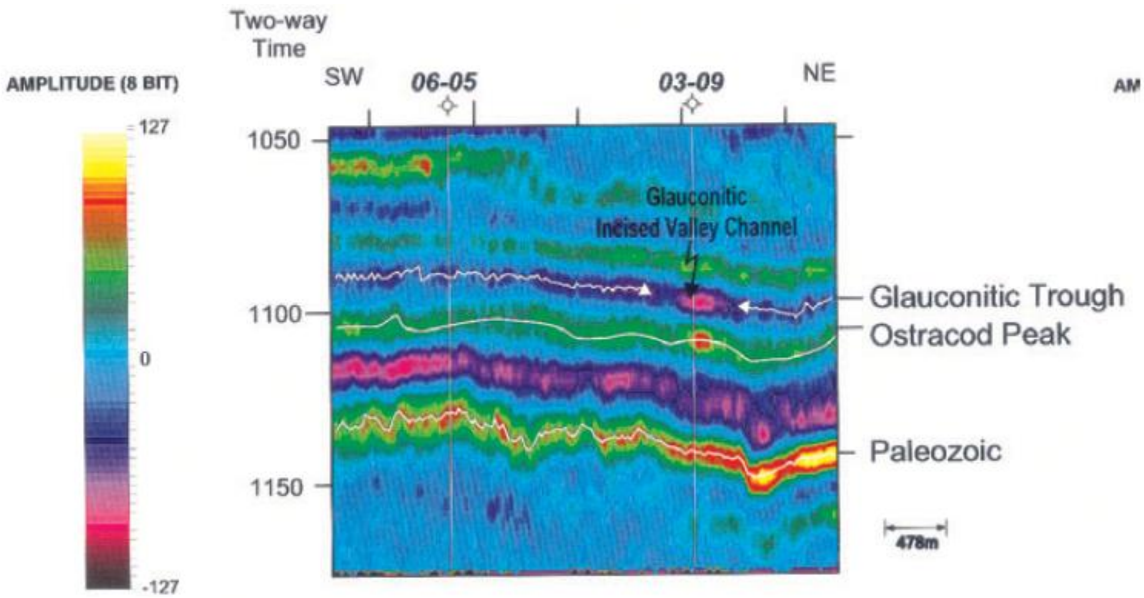


Figure 7. Two amplitude anomalies seemingly indicative of an incised valley sandstone (Mawdsley et al 1997).

Based upon these anomalies, the target was originally interpreted as a porous sandstone up to 22 meters in thickness in a channel system up to 300 meters wide and greater than 8 kilometers in length. The result of this interpretation was an economically developable reservoir. Two wells were drilled under the impression of a producible sandstone, but instead of a reservoir, they encountered a thin layer of carbonaceous shaly mudstone. Through reanalysis of sonic, density, and gamma changes on logs and correlation of these logs to new modeling of the seismic data, it was determined that the two anomalies were due to a lithologic change rather than to the presence of a reservoir. This seismic signature was determined to represent a thin carbonaceous shale-filled channel extremely similar to the signatures of thick incised valley reservoirs. This example demonstrates the potential pitfalls of seismic signatures because different features may exhibit similar geophysical signatures, especially through complex interactions with other structures. The premature acceptance direct hydrocarbon indicators, such as these anomalous bright spots, can lead explorationists to drill unproductive wells (Harilal and Biswal 2010). Mawdsley et al. (1997) note that the acquisition of higher resolution 3D seismic and incorporation of shear wave data may bring clarity to these cases.

In addition to the misidentification of seismic signatures, velocity changes across faults can create the impression of nonexistent structures that can pose a costly pitfall to interpreters. This particular pitfall, known as a fault shadow, occurs because of the differential velocity of seismic waves as they travel across rock layers with different characteristic velocities. Simplified models in Figure 8 by Trinchero (2000) illustrate how these pitfalls can arise from normal faults and reverse faults respectively.

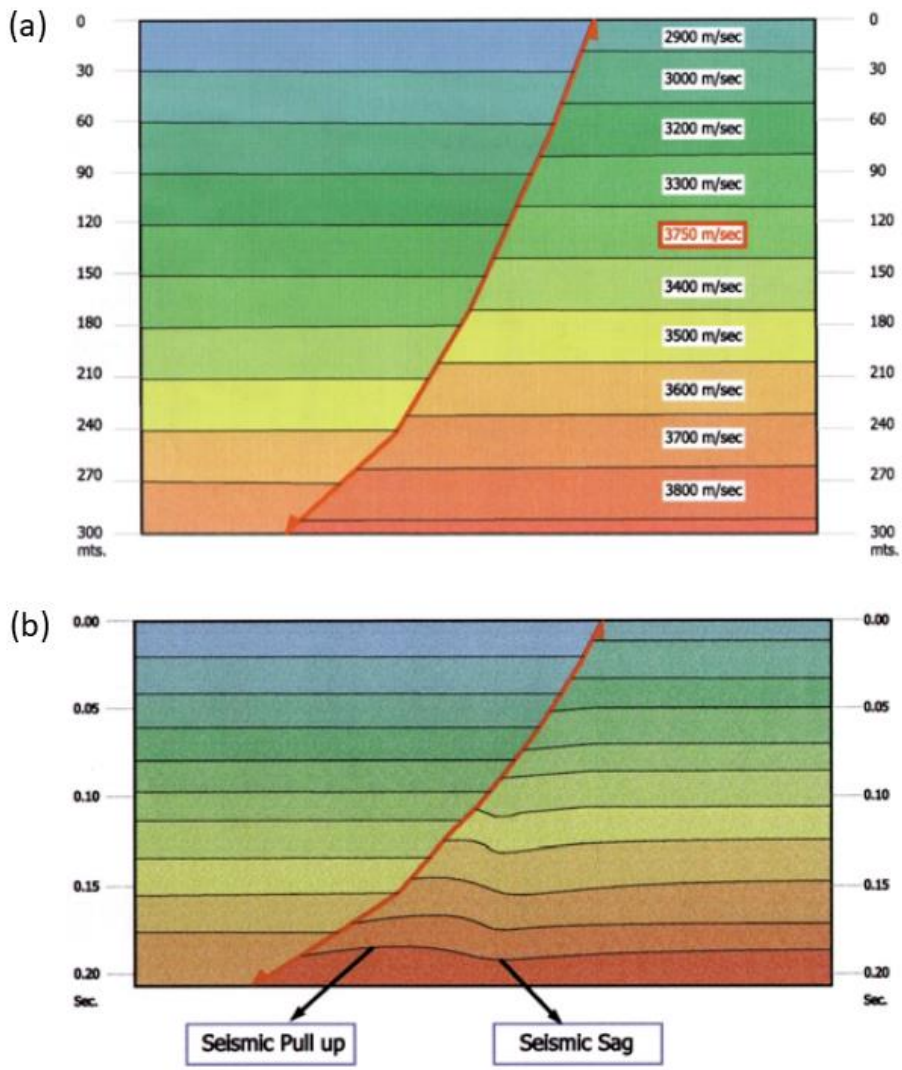


Figure 8. The fault shadow pitfall of a normal fault. (a) A geologic model in depth depicts true structure, (b) a geologic model in time in which a velocity-pull creates a false structure (Trinchero 2000)

The first model constructed in Trinchero (2000) features a normal fault cutting through a series of rock layers that feature a general trend of increasing seismic velocity with depth. Within this progression, however, there is a break in the pattern with the inclusion of a high-velocity layer between two layers of lower velocity. The juxtaposition of the varying seismic velocities across the fault causes layers beneath it to exhibit a seismic pull-up and a seismic sag, or push-down. The combination of these apparent features is an apparent anticline, which could easily be misinterpreted as a trapping mechanism for hydrocarbons.

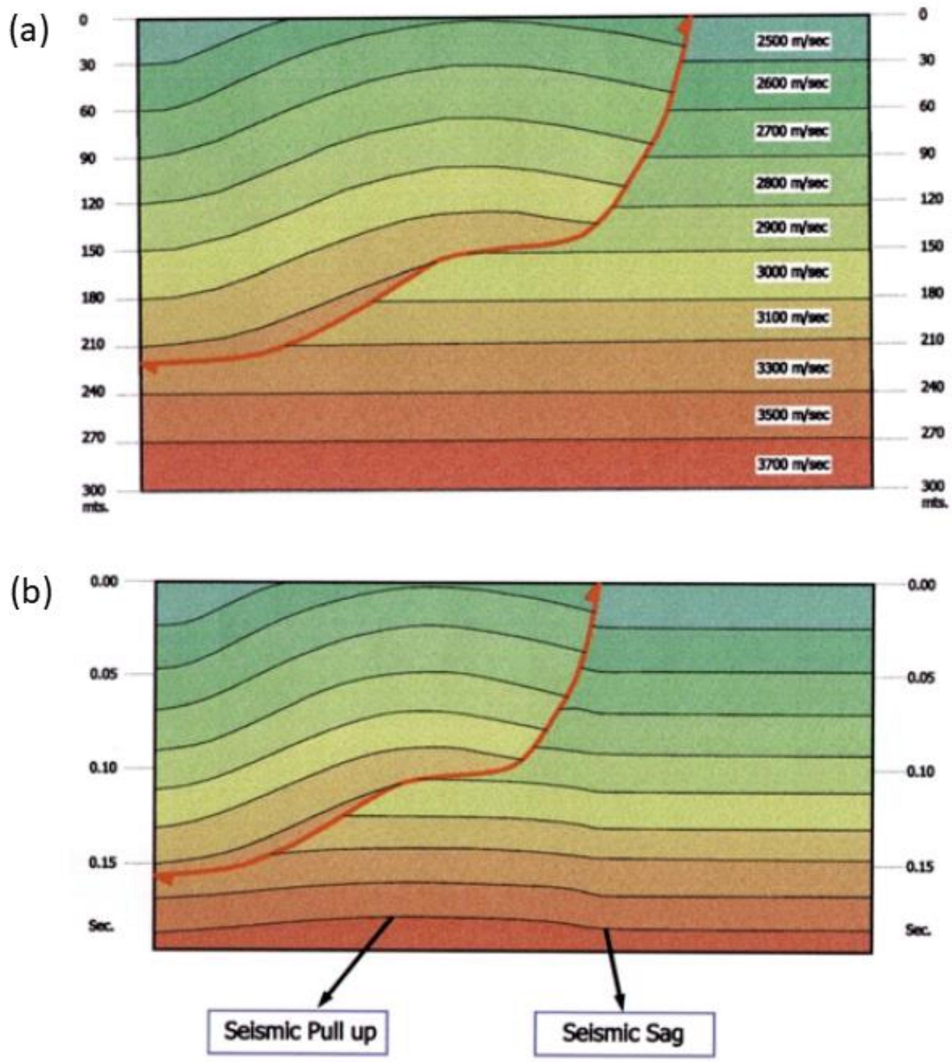
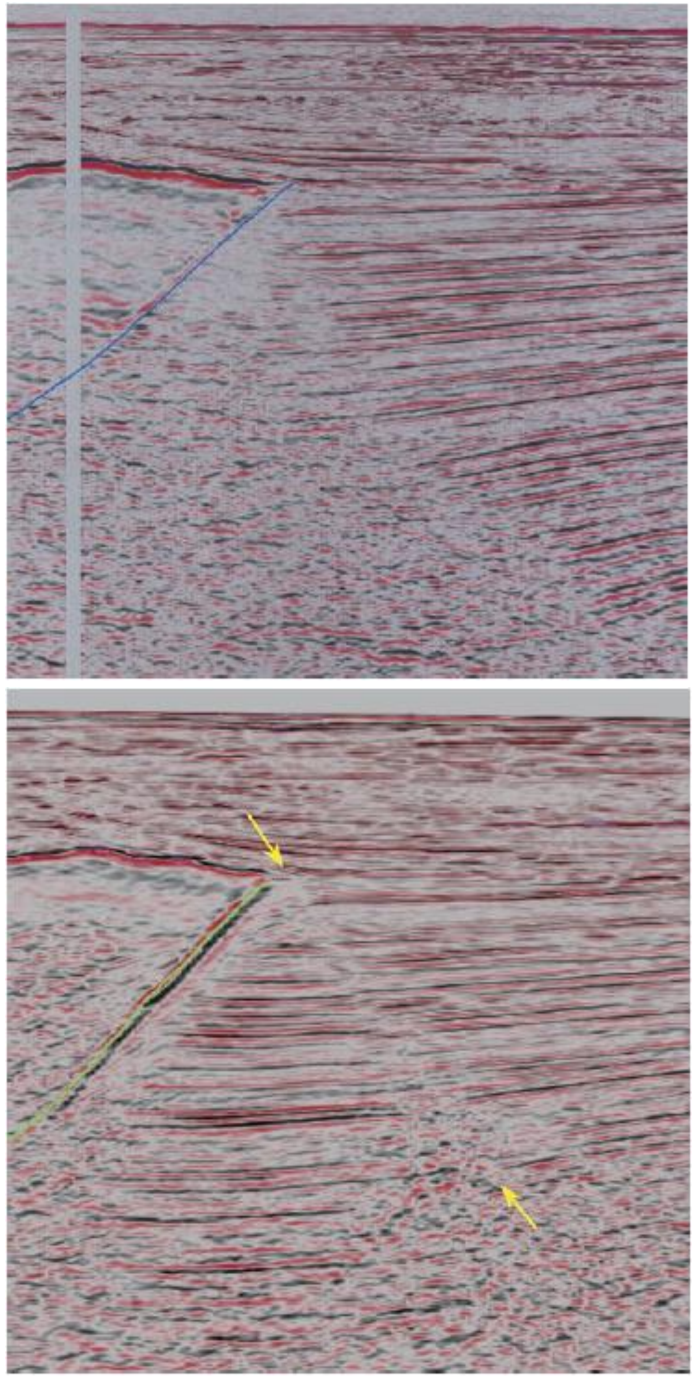


Figure 9. The fault shadow pitfall of a reverse fault. (a) A geologic model in depth depicts true structure, (b) a geologic model in time in which a velocity-pull creates a false structure (Trinchero 2000)

The fault shadow phenomenon can also occur in association with reverse faults. The same effect of seismic pull up and seismic sag occurs from the lateral velocity contrast, and in some cases, it can be even more extreme in these compressive regimes due to the large displacement as a result of the reverse fault. Though extremely simplified for presentation in these models, the fault shadow phenomenon shows the pitfall of mistaking time structures present in seismic data for a perfect representation of geologic reality.

5.2 Pitfalls Associated with Geometry

In the case of velocity-related pitfalls, errors were the result of the behavior of seismic waves as they travelled through the subsurface. In other cases, the geometry of bodies in the subsurface can also contribute to these pitfalls. Geometry in this sense refers to the shape or structure of geologic features. Common culprits in these cases are salt bodies because of their compressibility and fluidity which leads to complex shapes with steep angles (Jones and Davison 2014). One potential pitfall resulting from such salt bodies is demonstrated by Herron (2000). In this example taken from the Gulf of Mexico, a wedge-shaped salt body cuts into a series of sedimentary layers. Multiple images were produced from the acquired data through different post- and pre-stack depth processing. Two of these images are included in Figure 10 for examination.



(a) (b)

Figure 10. Geometric seismic pitfall of a steeply dipping salt body. (a) Post-stack depth migrated image and (b) Pre-stack depth migrated image (Herron 2000).

The two images in Figure 10 appear nearly identical save for an apparent fault present in Figure 10(b) that is indicated at its top and bottom boundaries by yellow arrows. In the absence of more information, this discrepancy would create a conundrum concerning the presence or absence of the fault in reality. In this case, however, the fault was concluded to be an artifact because of its apparent nature as a reverse fault, which is not typical of the Gulf of Mexico, and because of its coincidental termination at the top of the salt wedge. This artifact was created because of the improper application of a velocity model used to migrate the data into a depth model, and the migration operator of the model is itself dictated by the geometry and position of the salt body.

5.3 Pitfalls Associated with Recording and Processing

The last category of pitfalls is perhaps the most insidious because it arises through decisions made in the preparation of the seismic data. The choices made at these junctures can have downstream effects that can create artifacts or complications in the final seismic images that can severely hamper or impede interpretation. An example of this pitfall has already been demonstrated by through the migration of data affected by salt bodies in the Gulf of Mexico (Herron 2000). Though the pitfall was rooted in the steeply dipping angle of the salt body, the decision of how to process the data was also a factor in the presence or absence of the artificial fault. When the seismic image was prepared using post-stack processing, the fault did not appear. However, pre-stack processing introduced the anomaly into the data. This example serves as a reminder that the seismic image is far from perfect as a representation of geological reality and that the acquisition and processing of data has crucial effects on its subsequent interpretation.

In addition to localized artifacts observed in the final seismic image, pitfalls can also manifest as a wholesale degradation in the quality of the seismic image. Typically, geophysicists aim to utilize data with a broad range of frequencies to search for subtle geologic information that can inform explorationists about the hydrocarbon potential of a target. However, this strategy is not a catch-all method of seismic processing that works for all exploratory purposes. Hardage (2015) recounts an example of this pitfall in a lookback on a study of the Delaware Basin in west Texas. In the area considered, there was a poor source-to-noise ratio, and so the goal of this study was not so much fine-scaled analysis of minute details but rather a broader look at the structural features of the basin. For this purpose, the use of a broad frequency spectrum was counterproductive, as depicted in the comparison in Figure 11.

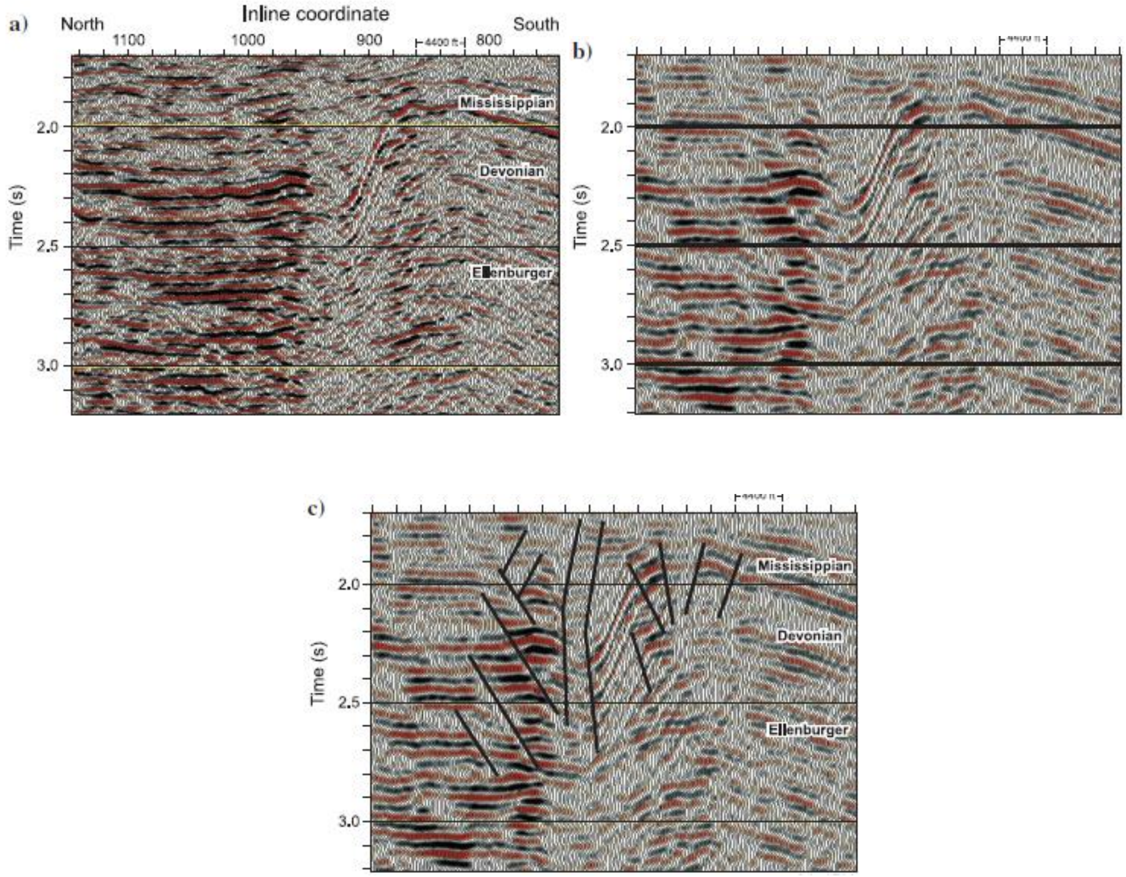
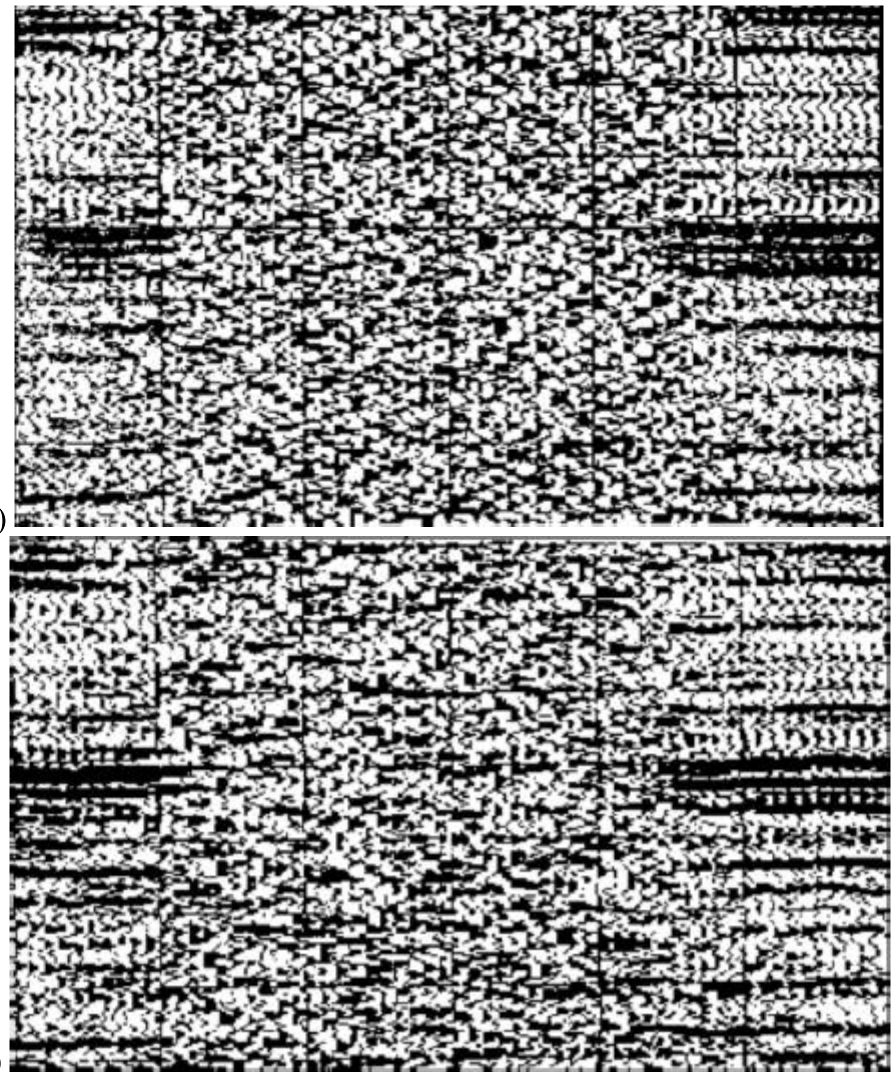


Figure 11. The pitfall of a broad frequency spectrum. (a) A sample of a broadband frequency spectrum (8-80 Hz) image. (b) The same sample depicted in a narrowband frequency spectrum (8-16 Hz) image. (c) Fault interpretations on the narrowband image. (Hardage 2015).

Comparison of the above figures illustrates the importance of setting the proper parameters for the task. In this area of poor source-to-noise ratio, the wider frequency obscures some of the structure, as best illustrated in the left half of the image. In contrast, the narrower frequency reveals cleaner disruptions in the data that can more easily be recognized as faults. This example demonstrates that a processing technique that might be applicable in one situation, or even the majority of situations, may not be the ideal technique for all cases.

Although examples of pitfalls arising from inadequate processing have been showcased so far, it is also possible for the other extreme to create interpretation pitfalls – it is possible for data to be overly processed such that it distorts the features it was meant to image. Hill (1999) demonstrates this principle with a simple model taken to an extreme case. In this example, Hill replaces the traces of a series of consecutive shots with random noise to create a meaningless data set devoid of any true signal. This noisy data set is then subjected to a static correction program meant to shift the traces to account for factors such as weathering or topography that might cause the traces to contain travel time artifacts. The initial noisy stack and the same data after a statics correction program are depicted in Figure 12.



a)

b)

Figure 12. The over-processing of data. (a) A stack in which the central shots have been replaced by noise. (b) The same stack after undergoing static correction. (Hill 1999).

Although the two images appear quite similar at first glance, Figure 12(b) shows some degree of lateral continuity that was absent in the pure noise. However, this supposed correction does not truly bring any clarity to the data, since there was no data to begin with. Though it is tempting to suppose that with enough processing power any problem could be solved, this example demonstrates that such brute force methods can do more harm than good when it comes to resolving data with low signal-to-noise ratios.

Chapter 6. The Value of Information in Exploration and Production

The discussion thus far has been fairly discouraging as it has focused on the weaknesses of seismic information that may give decision makers reason to be wary of potential errors in the interpretations produced by geoscientists. In spite of this pessimism, however, such data sets continue to find widespread use in practice. This is a telling clue that in spite of these misgivings, seismic information can offer benefits than outweigh its costs. Qualitatively, recognition of this concept is not lost upon those involved in the exploration process. However, pinning down this tipping point quantitatively is often a more challenging task. The solution to this problem is offered by the decision analysis concept of the value of information.

6.1 Information in the Context of a Decision

Although the term "decision" is used in common language, it is often difficult for most people to concretely define the term. In the field of decision analysis, a decision is defined as "an irrevocable allocation of resources, irrevocable in the sense that it is impossible or extremely costly to change back to the situation that existed before making the decision" (Howard 1966). Furthermore, every decision is composed of three parts which determine the best course of action for the decision maker: the available alternatives, the preferences of the decision maker, and the information relevant to the situation. The alternatives consist of the possible courses of action that can be exercised by the decision maker. The preferences are defined by the decision maker, and encode what he or she wants to achieve from the situation. Lastly, and of particular interest to this thesis, is the information. The model of the decision situation and its associated basis is illustrated in Figure 13.

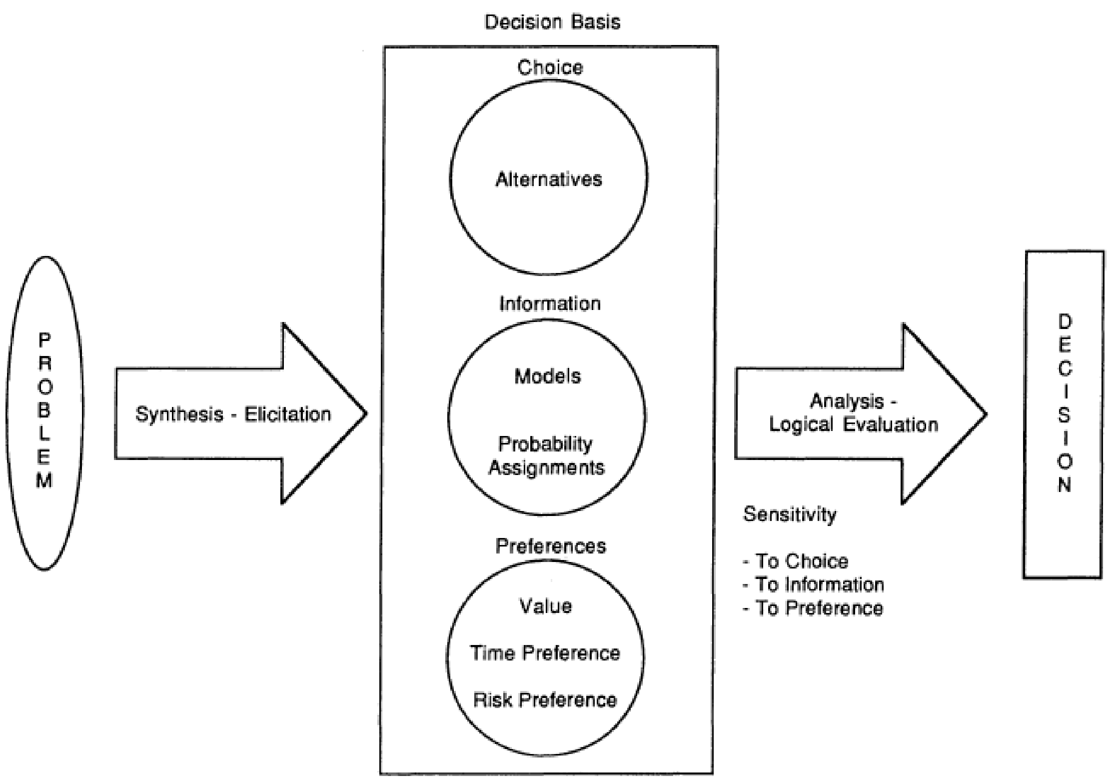


Figure 13. A model of the decision basis (Howard 1988).

The three elements of the decision basis are crucial in each and every situation demanding a decision. The alternatives lay out the paths available and the preferences provide a compass to determine which of these paths is most desirable. To continue with this metaphor, information provides the landscape and geography through which these alternatives traverse. It encompasses the facts and conditions relevant to the situation as well as the models, relationships between variables, and probability assignments that affect the final outcome of the decision (Howard 1988). In many cases of decision making, the primary goal of information is to reduce uncertainty and to bring clarity, but information is necessary for a variety of reasons as detailed by Repo (1989):

- Awareness or identification of the problem
- Definition or collection of relevant information
- Development of alternative hypotheses
- Evaluation of alternatives
- Selection of optimum solution or alternative
- Implementation [of the alternative decided upon]
- Review of the results or performance as a consequence of the implemented decision

6.2 The Value of Information

A common platitude among academics, notably scientists and engineers, is that more information is better. However, in practice, especially in the light of decision analysis, this platitude can be demonstrated to be false. For example, information that is irrelevant and has no bearing on a decision would not leave a decision maker in a better position upon reception. Furthermore, this assumes that the information would come free of cost. In reality, information gathering is often not free. In such cases, irrelevant information obtained at a cost can only be detrimental as it decreases value. Even in cases in which obtained information is relevant, if it costs more than the value it creates, it is a net value loss. These scenarios illustrate the fact that more is not always better when information is concerned, and furthermore, there may be some tradeoffs related to the acquirement of information. Together, these points suggest that there is a value of information that is determined by the interplay of its costs and benefits. Before considering a quantitative approach to assessing the value of information, it is helpful to establish a qualitative basis that defines when an information gathering test would add value to a decision. Bratvold et al. (2007) lay out four criteria that must be met for such a test to be deemed value-adding:

- Observable – A value-adding test must be observable to the decision-maker before the decision is made.
- Relevant – The test must possess some relation to the uncertainty of interest.
- Material – The test must have the potential to change the decision a decision maker would choose.
- Economic – The test must cost less than the value it creates.

The last criterion listed above that specified that an informative test must create more value than it costs to obtain, with the created value representing the namesake value of information (VOI). In general, the value of information is the price for information that would cause a decision maker to be indifferent between having and not having the information. In many cases in the petroleum industry, the value of information is given by the following equation:

$$
\begin{aligned}
&Value\ of\ Information \\
&\qquad = Expected\ Value\ with\ Information \\
&\qquad - Expected\ Value\ without\ Information
\end{aligned}
$$

This definition holds true in cases in which the decision maker is risk-neutral (Bratvold et al. 2007). For many companies and projects in the petroleum industry in which a single success or failure will not lead to total financial ruin, this assumption of risk-neutrality is applicable.

Because the exploration process is essentially a series of information gathering and synthesizing events that culminate in major, strategic decisions, the value of information concept factors heavily into the decision process of whether to gather more information in the form of additional geologic or geophysical surveys. This section will predominantly focus on seismic data sets, but it will also include a general discussion of the value of information in the oil and gas industry.

6.3 An Overview of Previous Work Examining the Value of Seismic Information

As previously described, the value of information is of great interest to decision makers, but it is the subject of limited study in existing literature. A previous review by Bratvold et al. (2007) revealed that for the time span ranging from 1962 to 2006, just 30 papers were published in the SPE (Society of Petroleum Engineers) database on the topic based upon a search for the following terms: "value of information", "information value", "data worth", "worth of data", "value of seismic", "value of 3D seismic", "value of 4D seismic", "value of logs", "value of core", and "value of well". Of these 30 papers, 17 were classified as illustrations of the concept, 7 as applications, and 6 as theoretic. It was noted that the low number of theoretic papers was expected, as the value of information concept was mature, and so there would not be major advancements that would be made in this arena. However, the low number of application papers, especially relative to the illustration papers, illustrates a disconnect between the recognition of the importance of VOI and its limited impact on the decision-making process. In spite of this historical underrepresentation in the SPE literature, the authors also note that the majority of this body of literature has been a part of a recent surge of interest in VOI at conference proceedings as illustrated in Figure 14. This suggests an increasing interest in the field, which is possibly indicative of additional growth in this body of literature in the future.

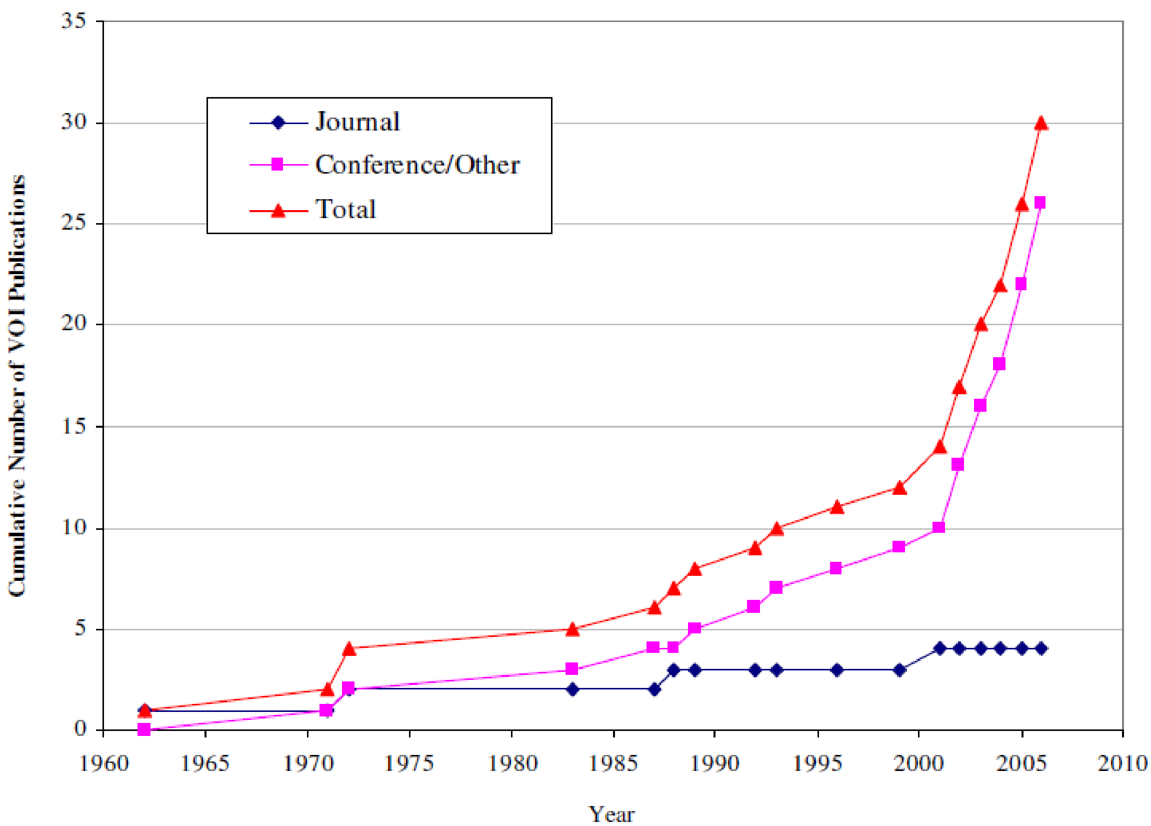


Figure 14. Cumulative total of VOI papers in the SPE literature (Bratvold et al. 2007).

The analysis of VOI done by Bratvold et al. (2007) was performed for VOI papers in any context in the oil and gas industry. A similar approach performed by Gray (2011) illustrated that this inattention to the value of information is especially pronounced among geoscientists when compared to petroleum engineers. This insight was found by performing a search for the combination of two sets of terms. The first of these sets pertain to terms that delineate particular disciplines in the exploration and production process. These terms are “engineering”, “seismic”, and “geophysics”. The second set of terms incorporates the economic aspect, and it includes “economic” and “success”. The results for search results of these combinations of terms in the SPE and SEG (Society of Exploration Geophysicists) is illustrated below in Figure 15.

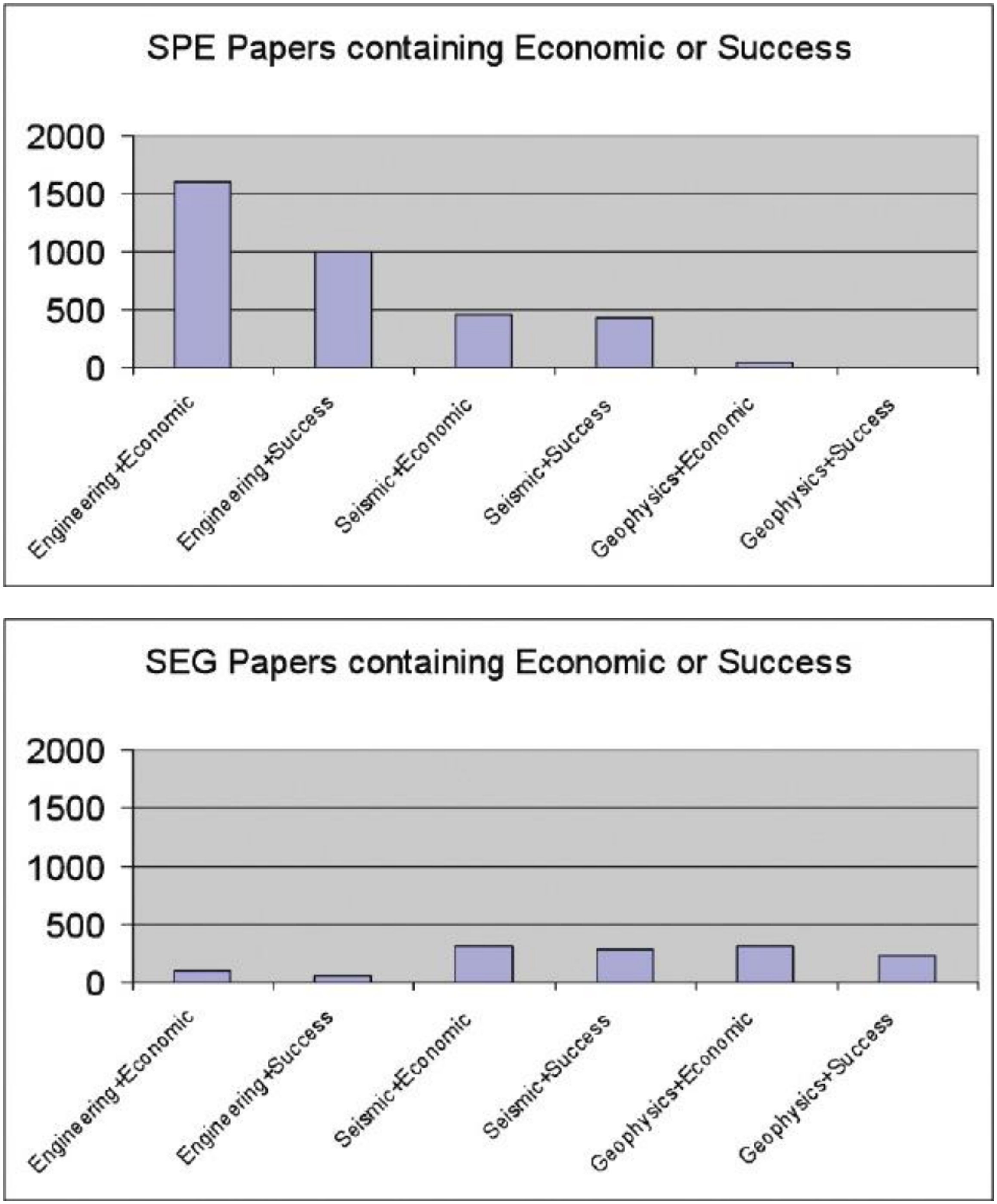


Figure 15. Existing literature on economics and success (Gray 2011).

Collectively, the number of papers dealing with these issues of economics is much greater in the SPE literature when compared to the SEG literature with about 3,500 and 1,250 results, respectively. In accordance with these different areas of focus, the combinations with the most representation were those that included the term "engineering", and this was especially the case in the SPE literature with marginal mentions in the SEG literature. On the other hand, search results for the term "geophysics" were least abundant in this study, with nearly the entirety of such mentions coming from the SEG literature. Search results for the term "seismic" fell in the middle ground of this analysis, suggesting that among geophysical techniques utilized in exploration, it was the predominant technique of interest for assessing the value of its performance. Furthermore, results for "seismic" were of roughly equal interest to authors in both the SPE and SEG database, suggesting that this was an area of overlap for both engineers as well as geoscientists and geophysicists. Even in this regard, however, this topic was of greater interest in the SPE literature. These results demonstrate that reviews of performance history and economic impact are more commonplace among engineers involved in the production phase than for geoscientists and geophysicists in the exploration phase.

The relative inattention dedicated to the value of seismic information highlights a case of misplaced priorities. A previous study has illustrated that the value of geological information is commonly understood as a measure of costs avoided (Haggquist and Soderholm 2015). This metric is fitting in the context of exploration as it is effectively impossible to control the distribution or amount of hydrocarbons in the subsurface. Instead, successes and failures are determined by the ability of companies to drill and produce from hydrocarbon-bearing reservoirs and to avoid drilling dry wells. In such projects, seismic acquisition and processing accounts for just about 20% of the total costs, whereas drilling accounts for about 75% of this total (Osypov et al. 2011). It is ironic then, that so little attention is paid to the economic value of seismic information, especially since additional investment at this stage of the project could circumvent the potentially fruitless costs of drilling.

Chapter 7. Incorporating Seismic Interpretation Uncertainty into Decision-Making

Previous sections in this work have discussed the process of petroleum exploration in its many dimensions. Before tying together all of these elements in a framework to assess seismic reliability and value, it is helpful to recount these discussions to understand how each contributes to the final decision to be made. First, we began with a discussion on the geological processes that constitute a petroleum system and the model that explorationists use to judge the potential of a prospect. We then discussed the geophysical underpinnings of seismic reflections, which constitute the most important data set available to these explorationists. The discussion of seismic reflections was followed by an analysis of some inherent weaknesses of seismic information as well as an introduction to the value of seismic information. In this section, we investigate the intersection of these elements in the light of value of information.

7.1 The Filter of Interpretation

The goal of any company is to deliver value to its shareholders through the planning and execution of profitable projects. From an upstream oil and gas perspective, this is accomplished through the drilling of wells to produce oil and gas. A simplified case of the decision of whether or not to drill a well and the resultant value of the decision can be modeled with a decision diagram, as illustrated in Figure 16. A decision diagram is an illustrative tool that enables decision makers to visualize the relationship between elements in a decision represented by differently-shaped nodes. Rectangles represent decisions to be made; ovals represent uncertainties affecting the decision; and rounded rectangles (more typically, octagons) represent values which the decision-maker seeks to optimize. Arrows connecting nodes represent a relationship between the elements that can include probabilistic dependence, influence, or timing.

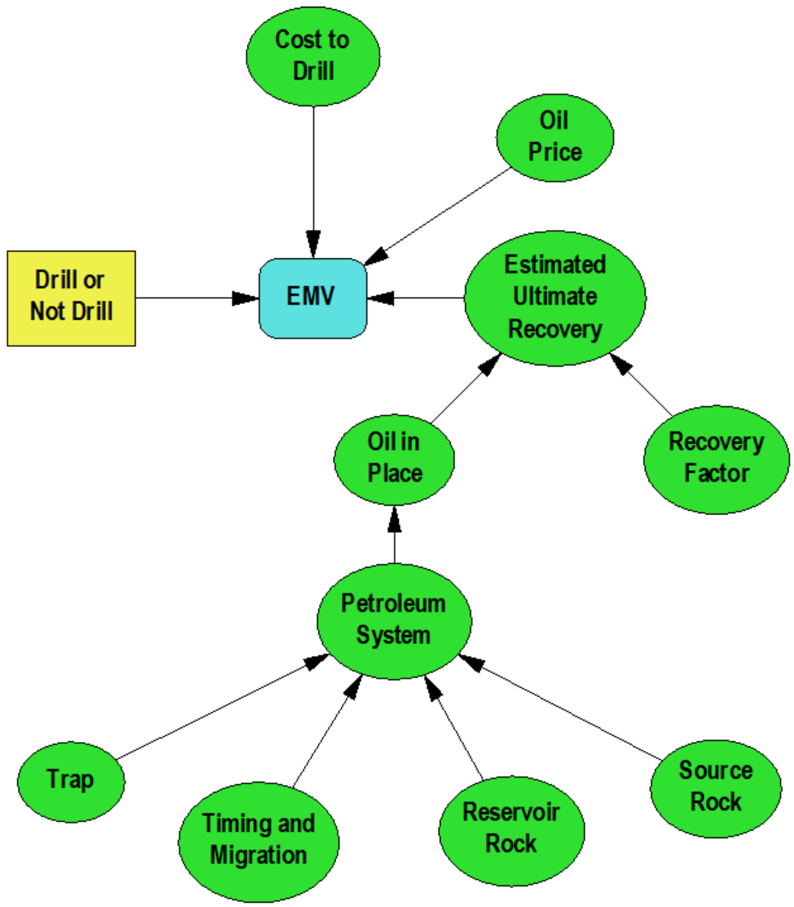


Figure 16. Decision diagram to drill without information

Without any information, the decision to drill and the final expected monetary value (EMV) is relatively uncomplicated, as there is only one node which requires action. All of the other nodes are uncertainties outside of the decision-maker's control. Of particular interest is the Estimated Ultimate Recovery (EUR), which is a measure of how much oil is expected to be produced after drilling the well. This is itself contingent upon the amount of oil in place, as dictated by the petroleum system, and the recovery factor of production engineers. Additional uncertainties affecting the EMV of this decision are the cost to drill and the price at which the oil can be sold. Of these many nodes, the only one within control of the decision-maker is the decision of whether or not to drill, and the absence of arrows leading from the uncertainties to the decision indicates that all of these uncertainties are unknown to the decision-maker at the time of the decision. Because of this lack of information, this diagram is only applicable in cases such as unexplored wildcat areas or infill drilling.

More typically, the petroleum industry standard of prospect evaluation follows a method similar to that reviewed by Otis and Schneidermann (1997) based upon assessments of the constituent elements of the petroleum system. These assessments allow for the expertise of geologists and geophysicists to be incorporated into the decision-making process, and in this way, the decision of whether or not to drill a well is informed by seismic information as illustrated in Figure 17.

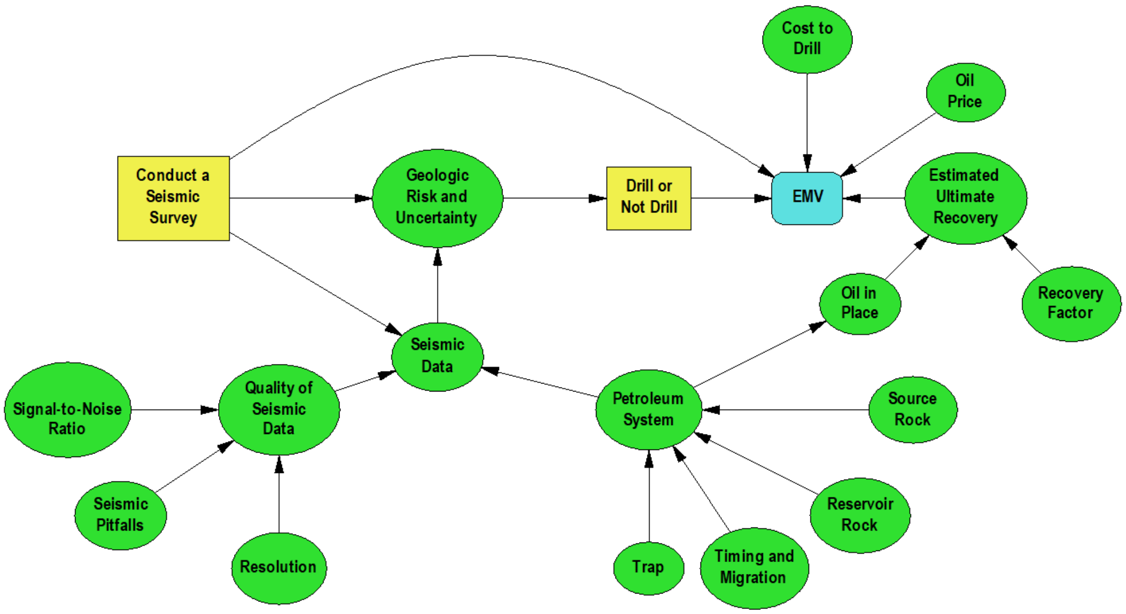


Figure 17. Decision diagram to drill with seismic information

This decision diagram is representative of the standard integration of seismic data sets into the decision making process. This case illustrates that a person may elect to conduct a seismic survey, thereby creating a seismic data set that can inform explorationists about geological risk and uncertainty based upon the quality of the seismic data and their assessments of the petroleum system. The EMV is still subject to the same uncertainties of the cost to drill, the oil price, and the estimated ultimate recovery as before, but in this case, decision-makers are not constrained to deciding blindly whether or not to drill. This has the obvious benefit of creating value by reducing the costs of drilling dry wells, but this representation of current practices omits a crucial element of the process.

To remedy this oversight, it is important to recount the weaknesses inherent to seismic data. Because of the indirect method of representation of the subsurface offered by reflection seismology, it is impossible to observe the rocks and fluids present, and so explorationists must rely on their understanding of geologic knowledge to create a model from the reflectors. As a result of the limited information available and the myriad interpretations hypothesized by multiple experts, these models are understood to be imperfect, uncertain, and liable to error. Traditionally, this recognition of uncertainty has been captured in the probabilities assigned to the elements of the petroleum system which informs the geologic risk and uncertainty. However, this method disregards the human element of interpretation, which is introduced below in Figure 18. Leaving out interpretation from the decision diagram is an acceptance of the results at face value, thereby providing an overly optimistic assessment of geological risk and inflating the EMV of the project.

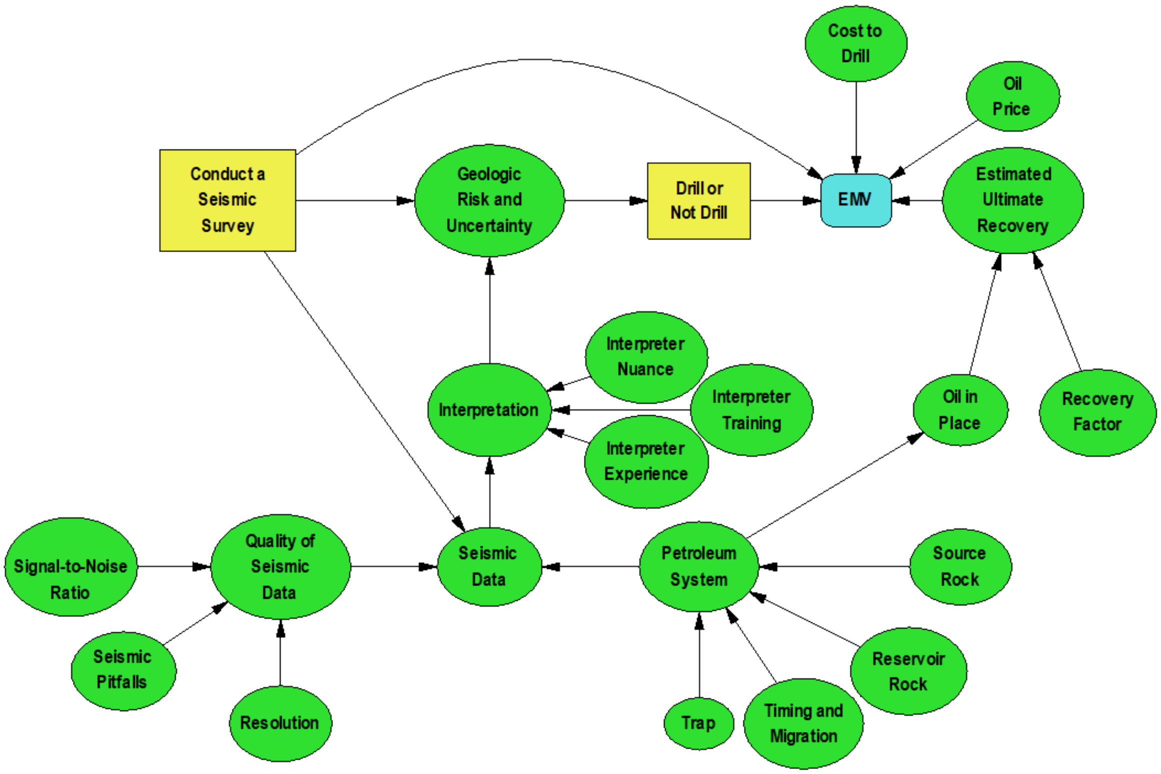


Figure 18. Decision diagram to drill incorporating interpretation uncertainty

Structurally, this decision diagram is nearly identical to its precedent, with the exception of the inclusion of a group of uncertainties related to interpretation. With this inclusion, a more realistic and holistic view of the decision-making process in exploration is achieved. This decision diagram illustrates a number of spheres which influence success and failure in exploration. In the bottom left corner, the realm of geophysics determines the quality of the seismic data produced. In the bottom right corner, geological structures processes and their interactions determines the character of a petroleum system. Moving upwards, the efforts of engineering influences the amount of oil recoverable based upon the oil in place and the recovery factor. Lastly, economic factors such as the cost to drill the well and the price of oil cover the financial aspects of the drilling project. These different spheres are all of great interest to decision-makers, and are accordingly active areas of study. Noticeably absent from this list, however, is the interpretational factor, which essentially translates a seismic data set into a metric which informs the decision of whether or not to drill to optimize the EMV of the project. Although a limited body of literature has been devoted to this field (Bratvold et al. 2007; Gray 2011), this interpretational factor remains a marginal player in the context of the exploration process relative to the other fields. Addressing the dearth of inquiry and integrating the uncertainty of interpretation has the potential to create value for explorationists.

7.2 Assessing Interpretation Reliability

A common problem facing any information gathering scenario in decisions with uncertain outcomes concerns to what degree the results of a test can be trusted. In the high-stakes world of petroleum exploration, this is especially true. As previously mentioned, the major benefit of geological information is often manifested in avoided costs (Häggquist and Söderholm 2015), and so the overestimation of interpretations may undercut this value. Motivational and cognitive biases may exacerbate this optimism (Montibeller and von Winterfeldt 2015). Therefore, it is important for decision-makers to apply a corrective factor to the geologic risk determined by interpreters. This section will qualitatively discuss different strategies that can be used to determine such a corrective factor.

One strategy to find this corrective factor is to perform historic lookbacks of past successes and failures of risk and uncertainty assessments and resultant production rates. This is a subject that is understandably absent from scientific literature, as these data sets and interpretations are highly valuable trade secrets (Cathey 2014). Even within companies, however, these reviews are not regular practice. A potential model by which this lookback can be executed can be adopted from applications in other fields, as demonstrated by Bickel and Kim (2008) and Bickel et al. (2011). In these analyses, the authors analyzed the probability of precipitations as predicted by different weather forecast providers. These analyses graded the performance of the different providers by examining the frequency of the occurrence of rain for different predicted probabilities of precipitation. For example, a perfectly calibrated forecast of a 10% probability of precipitation will observe rain 10% of the time. Similarly, a 50% probability of precipitation will observe rain half of the time, and so on for all forecasted values. As these forecasts were imperfect, the observed occurrence of rain deviated from the predictions. These predictions can then be scored by the amount by which the forecasts reduces the uncertainty about the probability of precipitation. More importantly, these results can then be used to better update beliefs based upon the correlation of the forecasts and the observations. Although this method was originally applied in a meteorological setting, there is merit to adopting it for exploratory purposes. At their cores, these predictions are identical in that they are sources of imperfect information that have a grounding in natural sciences that are filtered through human interpretation. Petroleum companies can use past interpretations and compare those predictions to the amount of oil and gas actually produced. One caveat that must be addressed is that in the weather cases, the prediction and observation of precipitation was assessed on a binary case of occurrence or nonoccurrence. In exploration, this binary case can be utilized to assess geologic risk concerning the presence or absence of petroleum. For decision-making purposes, however, more resolution is needed about the reserve sizes to determine geologic uncertainty. A possible solution to this problem is to refine the categorization from a binary case of occurrence to a discretization of possible outcomes that encompass both the occurrence of oil and the amount present given occurrence (Bickel 2012).

A similar strategy to assessing the reliability of a team of explorationists is to create a set of synthetic data that can administered to the team for their interpretation. Although this lacks the realism of the historical lookback, this approach offers some benefits of its own. By creating a model, the creators have complete control and knowledge of parameters and elements such as source to noise ratio, pitfalls, and the constituents of the petroleum system. Based upon the performance of the team on this test data, the administrators can more precisely judge the relative strengths and weaknesses of the interpreters. For example, the team may have an affinity for identifying faults and structural traps, but a deficiency at judging the source rock. In this way, decision makers can analyze the particular nuances of an interpretation and tailor adjustments to the risk and uncertainty accordingly.

7.3 Incorporating the Filter of Interpretation and the Value of Information

The following two sections will demonstrate the incorporation of interpretation uncertainty. However, without actual historical production values for consideration, it is impossible to execute the historical lookback strategy described above. In lieu of such data, this section will consider a hypothetical example for illustrative purposes.

One method to update one's belief in the light of new information is through the use of Bayes' rule (Houck 1999). Bayes' rule is given by the equation:

$$new\ p(Model\ M) = old\ p(Model\ M) * \frac{probability\ of\ observing\ the\ indicator\ if\ M\ is\ true}{total\ probability\ of\ observing\ the\ indicator}$$

This rule states that by observing a new piece of information, the new probability that we should assign to a particular model of interest, Model M, is found by multiplying the old probability prior to the acquisition of new information by a ratio related to the indicator's probability of being observed. The numerator of this ratio accounts for the effect of false negatives. The denominator is the probability-weighted average that the indicator may be observed in other models, and it therefore accounts for the effect of false positives.

In this example, consider a team of explorationists who classify the results of their interpretations into "No Reservoir", "Small Reservoir", and "Large Reservoir". In the past, this team has been correct in their interpretations 80% of the time. That is, when the team predicted "Large Reservoir", the results of drilling confirmed the presence of a large reservoir 80% of the time. For the remaining 20% of the time that they were incorrect, they were equally likely to have misinterpreted the data between the remaining two possibilities. In this particular scenario, geological priors have lead the team to believe that there is a 15% probability of a large reservoir, a 25% probability of a small reservoir, and a 60% probability that there is no reservoir in a site of interest. In this case, it is not sufficient to assume that because the interpreters have identified a "Large Reservoir", there is an 80% probability they are correct. In order to find how likely such a result would be, it is necessary to account for the geological priors and perform a Bayesian tree flip, as shown in Figure 19. This method is a graphic representation of Bayes' rule described above.

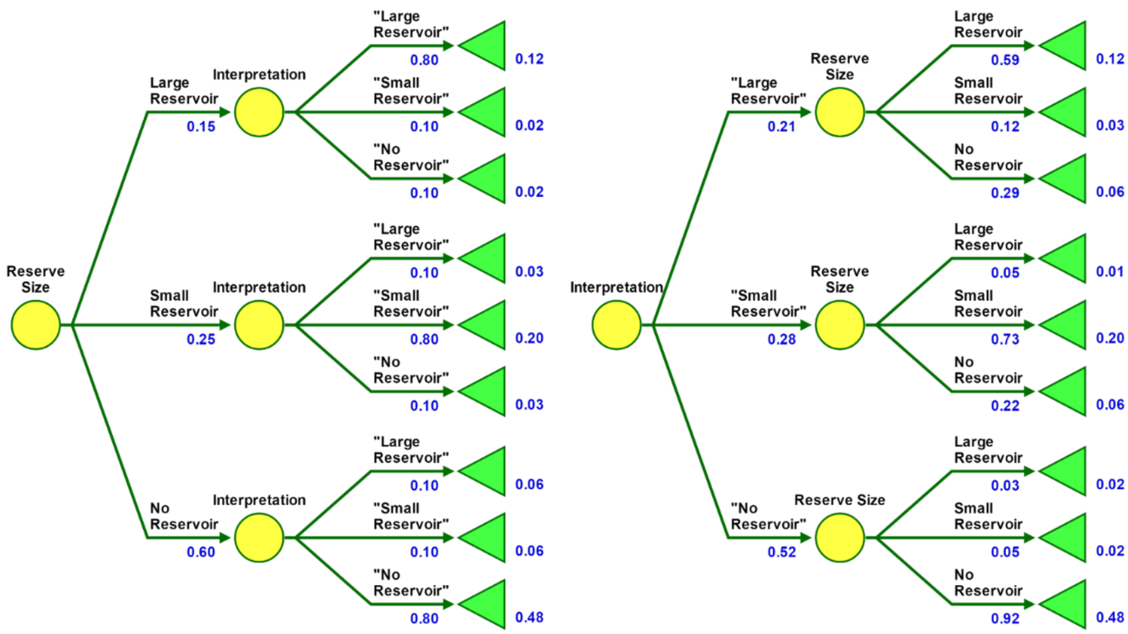


Figure 19. Bayesian tree flip of interpretation example

The tree on the left is given in assessed form, which represents how information is provided. The tree on the right is the inferential form, which enables decision-makers to make inferences about the reservoir presence and size based upon the prediction. A Bayesian tree flip is necessary to convert from one form of the tree to another. This is performed by finding the probability of each combination of predictions and outcomes to find the joint probabilities for each combination. These joint probabilities for each prediction are then added to find the probability that each prediction will be made. This is known as the marginal probability for the prediction. Lastly, the joint probability for each outcome of reservoir size is divided by the marginal probability of its preceding prediction in order to find the marginal probability of the reserve size given a particular prediction.

As demonstrated by the Bayesian tree flip, each interpretation result is weighted differently because of the effect of the geological priors. These differences expose the folly of accepting the geological risk and uncertainty at face value. In none of these three cases does an 80% accurate prediction observe that outcome 80% of the time. A large reservoir should only be expected 59% of the time when a “Large Reservoir” is predicted. In contrast, a “No Reservoir” prediction is correct 92% of the time, and a “Small Reservoir” prediction falls in the middle, as it is correct 73% of the time.

The differences between these probabilities can be contextualized in a decision-making scenario by attributing values to the payoffs for each result as well as a cost to drill a well. In this scenario, assume a well costs $120 MM to drill. In the event a large reservoir is discovered, the payoff is $250 million. If a small reservoir is discovered, the payoff is $150 million. And lastly, if no reservoir is discovered, there is no payoff. These values and the probabilities previously calculated can be used to build the decision tree in Figure 20. The expected value for each uncertainty node is the probability-weighted average of each of its associated outcomes’ results. The value for each decision is always the greatest value among the possible alternatives.

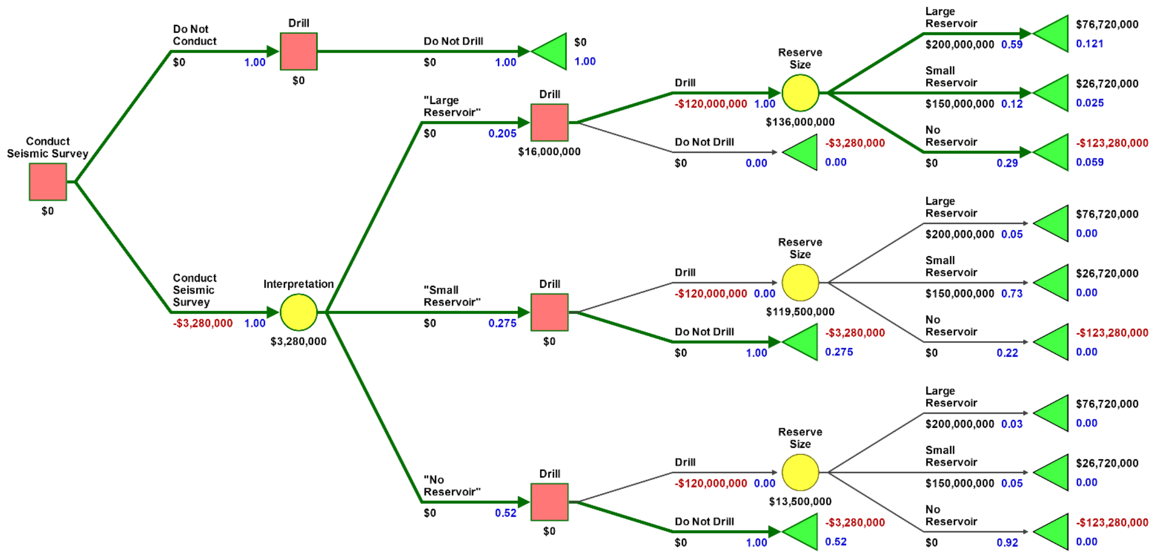


Figure 20. Decision tree for interpretation example

In this example which assumes risk neutrality, the decision-maker would only drill if the team of interpreters predicted “Large Reservoir”. This is because based upon the known information about the probability of each outcome, the value of each outcome, and the cost to drill, this prediction is the only outcome with a positive expected value at $16 MM.

In addition to informing a decision-maker’s best alternative given a particular prediction, building a decision tree is also a crucial step in determining the value of information. As previously mentioned, the value of information is the amount that would make a decision-maker indifferent between alternatives in which he or she would have to make a decision without information and when she would have information. For risk-neutral decision-makers, this amount is the difference between the two scenarios. In this case, that amount is $3.28 MM, which is the value created by the decision to purchase and interpret the seismic interpretation, with an understanding of its imperfection.

The central concept of this section thus far has been the uncertainty of interpretations and the necessity of recognizing these imperfections. For illustration of this concept, it is helpful to analyze the case in which the interpretations are taken at face value, with no recognition of their uncertainty. This decision is illustrated in Figure 21 below.

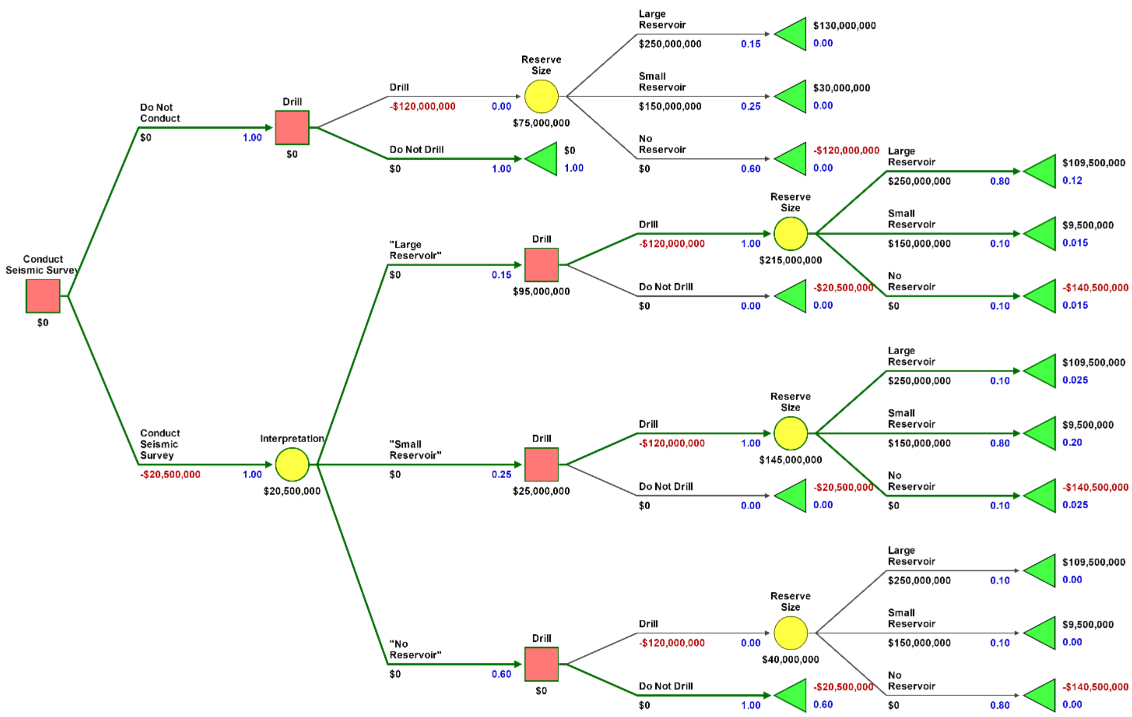


Figure 21. Decision tree with interpretation uncertainty omitted

With the uncertainty omitted, the value to drill given a "Large Reservoir" prediction increases to $95 MM. A more significant change, however, is the decision to drill given a "Small Reservoir" prediction. In the previous case, based upon the uncertainty of interpretation, the decision to drill resulted in a negative expected value. Here, however, the value to drill is \$25 MM. As a result of these changes, the value of these assumedly perfect interpretations is \$20.5 MM. In effect, neglecting this uncertainty inflates the value of the interpretations by \$17.22 MM. For the case in which a “Large Reservoir” is predicted, this omission is not as impactful, because the decision-maker would have drilled in either case. For a “Small Reservoir” prediction, however, this can be much more costly, because the decision of whether or not to drill differs with the treatment of the interpretation.

Chapter 8. Conclusions and Future Work

The standard system of exploration prospect evaluation provides a powerful framework for assessing the elements of a petroleum system that enables knowledge of geological models to inform decisions of whether or not to drill a well. The most ubiquitous source of data that forms the basis for these models is that of seismic information, which consist of the signature of acoustic waves reflecting off of layers in the subsurface. Though reflection seismology offers an unprecedented view of the subsurface, the method is prone to error because it is not able to offer investigators direct observation of the contents of the earth. Because of this indirect representation, anomalies in seismic data may arise that do not reflect the truth of the subsurface. Furthermore, interpretations from the data must be made, and these interpretations are affected by the mental models of explorationists who analyze the data. Consequently, interpretations are subject to personal nuances of the interpreter. As a result of these complications, it is nigh impossible that any model put forth by interpreters is absolutely representative of reality. However, the current practice of prospect evaluation assumes that all of the uncertainty of these interpretations is sufficiently captured in the explorationists' assessment of the geological risk and uncertainty, and that these metrics can be taken at face value when a decision about drilling is to be made. This process can lead to an inflated valuation of a drilling decision which may lead to a suboptimal decision being made. As a result, it is imperative for decision-makers to take into account the filter of interpretation which accounts for the past performance of a team of interpreters and incorporates this into future decisions. Doing so will create value by guiding decision-makers to an optimal alternative.

The concept of the filter of interpretation has been largely unexplored, and so it remains largely theoretical. Future avenues for study will rely upon more rigorous analyses using real data from historical production and synthetic data. Beyond research purposes, however, this concept is of particular importance to explorationists or decision-makers in any field relying upon data interpretation. Awareness of the reliability of uncertain information has important downstream effects on the value of a decision.

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Vita

Jonathan Ly was born and raised in Rosemead, California. As a child, he had a natural curiosity for all things science and a particular soft spot for dinosaurs. At the age of sixteen, he attended the University of California, Berkeley to study evolutionary biology and paleontology. While at the University of California, Jonathan worked for and conducted research with the Museum of Vertebrate Zoology and the University of California Museum of Paleontology while earning a Bachelor of Arts in Integrative Biology. It was through these experiences that Jonathan recognized the ability of and need for scientists to inform decision making. To this end, Jonathan enrolled in the Energy and Earth Resources (EER) graduate program at the University of Texas at Austin. Through EER, Jonathan took courses in geology and decision analysis. Though the transition was a challenging and demanding endeavor, these trials shaped him into a flexible and adaptive thinker. Following his graduation, Jonathan will pursue a career in oil and gas consulting.

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